Petrology of the Volcanic Rocks of the Region around Boulder Dam

A Thesis

Submitted in Partial Fulfillment

of the Requirements for the Degree

of

Master of Science

California Institute of Technology, Pasadena, California

by

Maurice Sklar

1938

MUDDY MTS.

VIRGIN MTS.

VIRGIN RIVER

BOULDER
CANYON

BLACK MTS.

FORTIFICATION
HILL

UPPER
BLACK
CANYON ↑

LAKE MEAD

BOULDER
DAM

COLORADO
RIVER

LAS VEGAS
WASH

SADDLE RIDGE
(TO BE ISLAND)

HEMENWAY
WASH

"FAULT"
CANYON

BOULDER
CITY

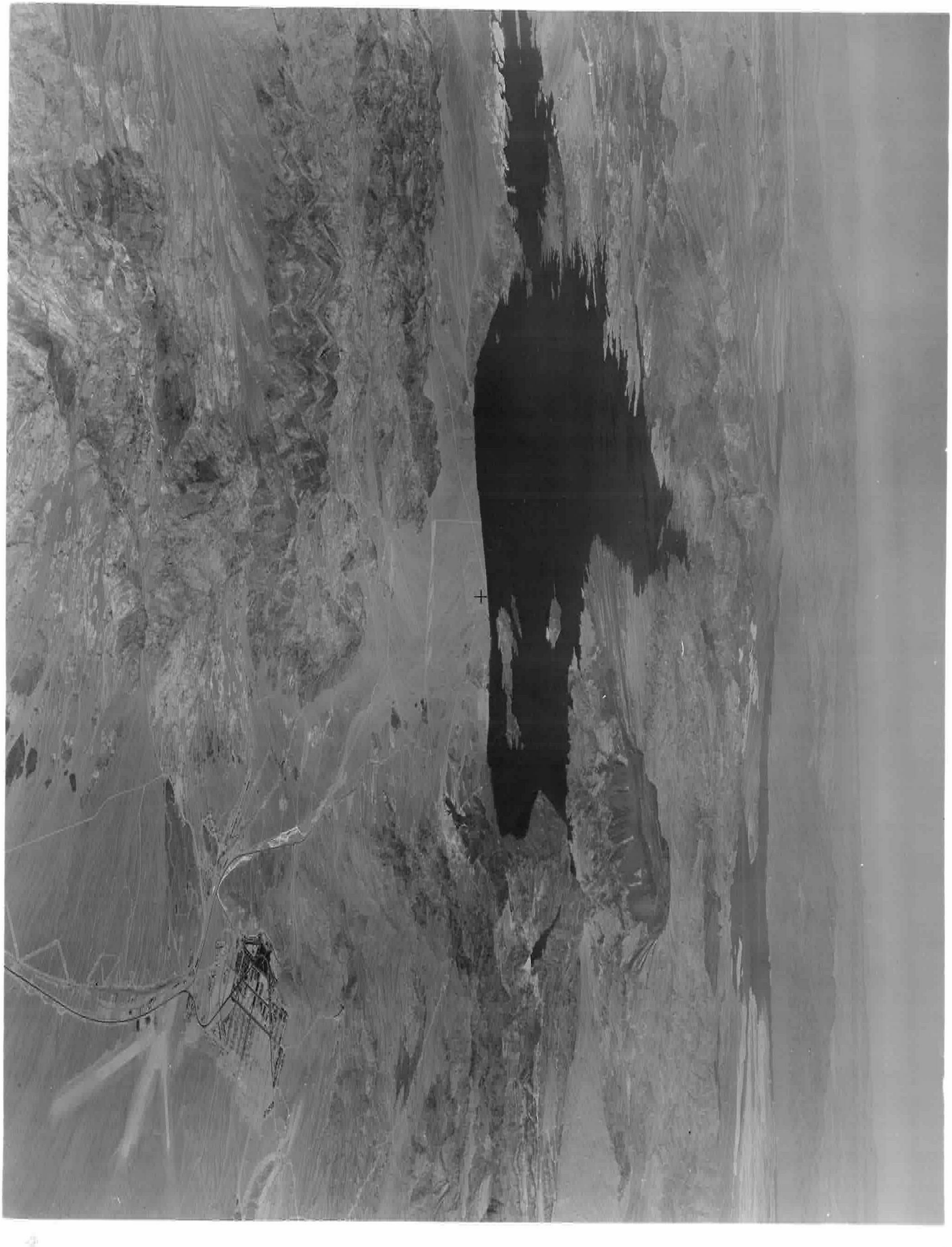
BOOTLEG
CANYON

TO LAS
VEGAS ↙

↑
ENE

AIRPLANE VIEW OF THE REGION AROUND BOULDER DAM

Taken April 21, 1937, by Fairchild Aerial Surveys.



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PETROLOGY OF THE VOLCANIC ROCKS OF THE REGION AROUND BOULDER DAM

(Abstract)

The rocks around Boulder Dam, which range from pre-Cambrian to Recent in age, are dominantly volcanic, but other rock types occur.

Pre-Cambrian granitic rocks occur in the Black Mountains, to the east; at Saddle Ridge is a chloritic schist, also pre-Cambrian. No known Paleozoic or Mesozoic rocks occur within the area.

The oldest of the early Tertiary (?) rocks is the Altered Monzonite Porphyry (?), which occupies a belt trending east-west across the area. This formation has been quite thoroughly hydrothermally altered. Intrusive into it is the Quartz-Monzonite, which occurs mainly south of Hemenway Wash.

The Older Volcanic Series, the most extensive formation in the area, occurs on both sides of Hemenway Wash, and south of Boulder Dam. It consists of a tilted series of andesite flows and intercalated sedimentary breccias. Between it and the Younger Volcanic Series, in Black Canyon, occurs the sedimentary formation, the Dam Breccia.

The Younger Volcanic Series occupies a depressed and tilted block, penetrated by Black Canyon, and rests unconformably or by fault contact on the Older Volcanic Series and the Dam Breccia. It consists of four volcanic extrusive and intrusive members, two tuff members, and two inter-volcanic sedimentary breccias. The volcanic members are all generally latitic in composition, being high in potassa and in total alkalies. These volcanic rocks are differentiation products of one primary magma.

The Fortification Hill Basalt and the conformable underlying Muddy Creek Formation are Pliocene, or possibly Pleistocene, in age. Quaternary deposits include terrace gravels of the Colorado River, and Recent alluvium.

Chapter I

INTRODUCTION

LOCATION OF AREA

The region to be considered in this report lies in Clark County, Nevada, and Mohave County, Arizona, and includes the area around Boulder (Hoover) Dam. The Colorado River, flowing through Upper Black Canyon, in which the Dam is situated, forms the Arizona-Nevada state boundary in this region.

Boulder City, Nevada, lying within the area mapped, is 23 miles southeast of Las Vegas, which is on trans-continental highway, U. S. 91. Boulder City can also be reached from Kingman, Arizona, some 90 miles to the south, on trans-continental highway, U. S. 66 (Fig. 1).

This region is important because of the existence in it of Boulder Dam, at present the largest and highest completed masonry dam in the world. Upstream from the Dam, Lake Mead, already the largest artificial lake in the world, is now being impounded. The supervision of an area of some 100 square miles, known as "Boulder Dam Recreational Area", (excepting the dam and power plant, and Boulder City, proper, which remain under the jurisdiction of the Bureau of Reclamation), is under the National Park Service.

The field work for this report was carried out during the summer of 1937, while the writer was connected with the National Park Service at Boulder City as a Student Technician.

This thesis has been undertaken in partial fulfillment of the requirements for the degree of Master of Science at the California Institute of Technology, Pasadena, California.

PREVIOUS WORK

Prior to a decade ago very little published information concerning the

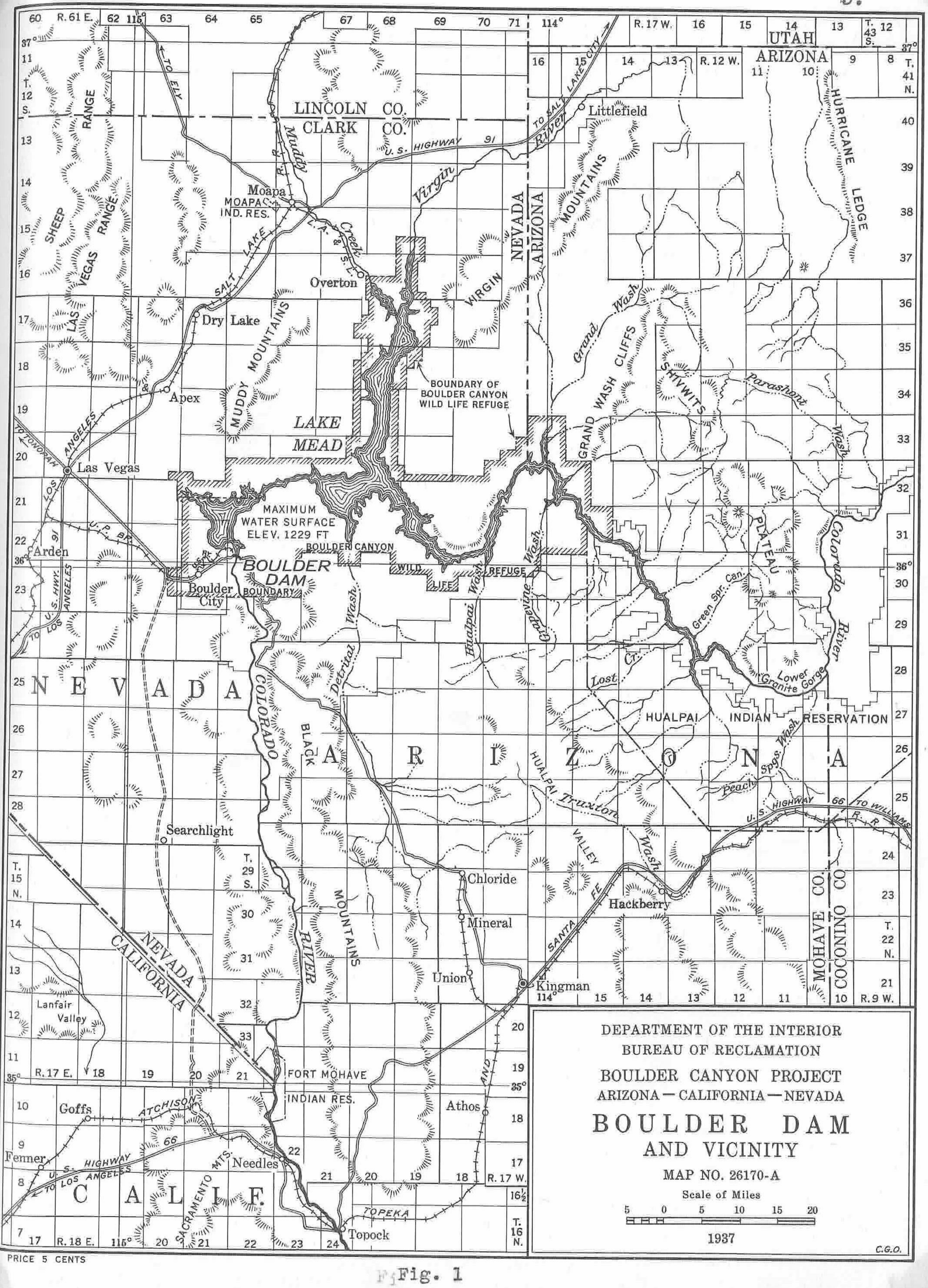
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
ARIZONA — CALIFORNIA — NEVADA
BOULDER DAM
AND VICINITY
MAP NO. 26170-A
Scale of Miles
5 0 5 10 15 20
1937
C.G.O.
NEVADA
ARIZONA
UTAH
CALIF.
LINCOLN CO.
CLARK CO.
MOHAVE CO.
COCONINO CO.
LAKE MEAD
BOULDER DAM
BOULDER CANYON WILD LIFE REFUGE
BOUNDARY OF BOULDER CANYON WILD LIFE REFUGE
MAXIMUM WATER SURFACE ELEV. 1229 FT
BOULDER DAM BOUNDARY
COLORADO RIVER
Colorado River
Virgin River
Muddy Creek
Grand Wash
Grand Wash Cliffs
Detrital Wash
Hualpai Wash
Grapevine Wash
Green Spr. Can.
Parashont Wash
Lower Granite Gorge
Lost Cr.
Truxton Wash
Peach Spgs. Wash
HUALPAI INDIAN RESERVATION
MOAPA IND. RES.
FORT MOHAVE INDIAN RES.
SHEEP RANGE
LAS VEGAS RANGE
MUDDY MOUNTAINS
VIRGIN MOUNTAINS
SHIVWITS PLATEAU
HURRICANE LEDGE
BLACK MOUNTAINS
HUALPAI VALLEY
SACRAMENTO MTS.
Lanfair Valley
Las Vegas
Boulder City
Overton
Moapa
Dry Lake
Apex
Arden
Searchlight
Littlefield
Chloride
Mineral
Union
Kingman
Hackberry
Athos
Goffs
Fenner
Needles
Topock
U.S. HIGHWAY 91
U.S. HWY. 91
U.S. HIGHWAY 66
TO ELY
TO SALT LAKE CITY
TO TONOPAH
TO LOS ANGELES
TO WILLIAMS
SALT LAKE
LOS ANGELES
L.A. & S.L. R.R.
U.P. BR.
SANTA FE
ATCHISON
TOPEKA
AND
R.R.
R. 61 E.
R. 17 W.
R. 12 W.
R. 9 W.
R. 17 E.
R. 18 E.
T. 12 S.
T. 29 S.
T. 43 S.
T. 41 N.
T. 22 N.
T. 15 N.
T. 16 N.
37°
36°
35°
114°
115°
116°
PRICE 5 CENTS

Fig. 1

petrology of the volcanic rocks of the Black Canyon region existed.

Ives (1)*, in 1861 first passed through the canyon and recorded the presence of great quantities of volcanic rocks in Black Canyon; his descriptions of the rocks of this region, as might be expected, are quite general.

In 1908 Lee (2) also visited the canyon, and made the first serious attempt to map the formations along the Colorado River. His conclusions, relating to the Black Canyon region, are confined to 8 printed lines.

During the early stages of the planning of Boulder Dam, Ransome (3) was engaged by the Bureau of Reclamation to make a detailed examination of damsites. His report, on the geology of the Upper Black Canyon damsite, at which Boulder Dam has been constructed, was the first to deal with the detailed geology of the volcanic rocks of the region.

His work has been confined, more or less, to the canyon and the adjoining areas. In this area, however, he has done much detailed work on the rocks of the Younger Volcanic Series, especially as regards the structural relationships of the various members of that formation; and much of the structural data of that series, presented in this paper, are due directly to Ransome.

In Ransome's paper the petrography of the Younger Volcanic Series has not been discussed nearly as completely as the structure, and only a small part of the petrographic data of the present paper are due to him. All partial chemical analyses quoted from Ransome are by M. G. Keyes of Washington, D. C.

The most recent and the most complete report on the region is by Longwell (4). This account gives the detailed geology of the reservoir

* denotes number of reference quoted in appendix.

floor, and notwithstanding the large area involved, goes into much detail regarding the Black Canyon region. This report has been very helpful in the matter of general geology.

BASE MAPS

Base maps available for field mapping were not entirely satisfactory, but were adequate for a general representation of the lithology and structure of the area. The following maps include parts or all of the area:

(1) The area is included by two United States Geological Survey topographic maps, the Saint Thomas, Nevada-Arizona, and the Camp Mohave, Arizona-Nevada-California sheets. These maps have a scale of 1:250,000 and a contour interval of 250 feet. Though these maps were reprinted in 1929 and 1937, respectively, the original survey was made before 1900, and their accuracy can not be too great for a region which covers only a small fraction of the total area of these two sheets.

(2) Parts of the areas of the above sheets adjacent to the Colorado River were resurveyed by the City of Los Angeles in 1926. The Metropolitan Water District has issued maps, with a scale of 1:125,000 and a contour interval of 100 feet, covering these areas.

From these maps the United States Geological Survey has reproduced topography in two advance sheets, the Boulder Canyon and Nelson quadrangles. These maps have a scale of 1:96,000 and the same contour interval, and are the best available maps for the purposes of this paper.

The township lines on these maps, however, are in error by almost one mile. It has been necessary to transfer township and section lines from the township maps to this base. The Nelson quadrangle, moreover, represents only the area on the Nevada side of the Colorado River, although the Boulder

Canyon quadrangle, to the north, includes both sides. Inasmuch as part of the field work for this report was done in that area in Arizona, south of latitude 36° 00' N, it has been necessary to transfer the topography from the Camp Mohave sheet to this base; this topography is necessarily generalized, however.

(3) A very excellent map for the region directly around Boulder Dam is the Brock and Weymouth map of the "Boulder Canyon Project", 1930, in 9 sheets, prepared from aerial photographs, with instrumental control on the ground. This map has a scale of 1:4800 and a contour interval of 5 feet. Unfortunately, the areal extent is limited to the region immediately adjoining the river, and does not in general extend above the 800 foot contour.

(4) The General Land Office has issued township maps, 1931, covering most of the area under consideration. The scale is 1/2 mile to the inch. This map proved of value in referring the locations of outcrops to the basis of section and township corners; this procedure was employed in giving locations of all rock specimens collected. The townships involved are:

T 22 S	R 65 E	Mount Diablo Meridian, Nevada
T 23 S	R 64 E	Mount Diablo Meridian, Nevada
T 22 S	R 64 E	Mount Diablo Meridian, Nevada
T 31 N	R 23 W	Gila and Salt River Meridian, Arizona
T 30 N	R 23 W	Gila and Salt River Meridian, Arizona

(5) In connection with the surveys for Boulder Dam, the Bureau of Reclamation has issued a map of the "Boulder Dam Project - The Vicinity of Hoover (Boulder) Dam", Map. No. 24,000, 1932. This map, with a scale of approximately 3.6 miles to the inch, has a contour interval of 500 feet. It has the advantage that both sections and townships, and also the Boulder Dam coordinate system for surveys, (on the basis of a certain point on top of the

dam having the coordinates 30,000' N and 50,000' W), are plotted on this same base, which has 15 minute intervals of latitude and longitude represented. Culture is also shown on this map. Were it not for the too large contour interval, an enlargement of the portion of the map around the dam might have proved satisfactory for the general representation of the geology.

(6) The United States Geological Survey and the United States Bureau of Reclamation have issued, 1924, a series of 21 maps, entitled "Plan and Profile of the Colorado River from Lees Ferry, Arizona, to Black Canyon, Arizona-Nevada, and Virgin River, Nevada". These maps include the area below 1250 feet, and have a scale of 2 inches to the mile, with a contour interval of 50 feet. The areal extent of sheet L, which includes Black Canyon, is too limited to be of value.

(7) The Soil Conservation Service of the Department of Agriculture has issued, 1937, the advance sheet of a topographic map of the Lake Mead Reservoir. This map has a scale of 1:12,000 and a contour interval of 5 or 10 feet. Sheets 5 and 8 of this series, which include the Black Canyon region, are quite excellent as far as they go; the area is mainly restricted, however, to the reservoir floor, and does not in general extend above the 1400 foot contour.

TOPOGRAPHY

The total area involved in this report is approximately 60 square miles; of this, however, most of the terrain is Recent alluvium, as occurs in Hemenway Wash, and other sedimentary formations. The actual extent of the bedrock is much less than the above figure.

The highest points within the area are the summit of Fortification Hill, the imposing flat-topped landmark northeast of Boulder Dam, whose

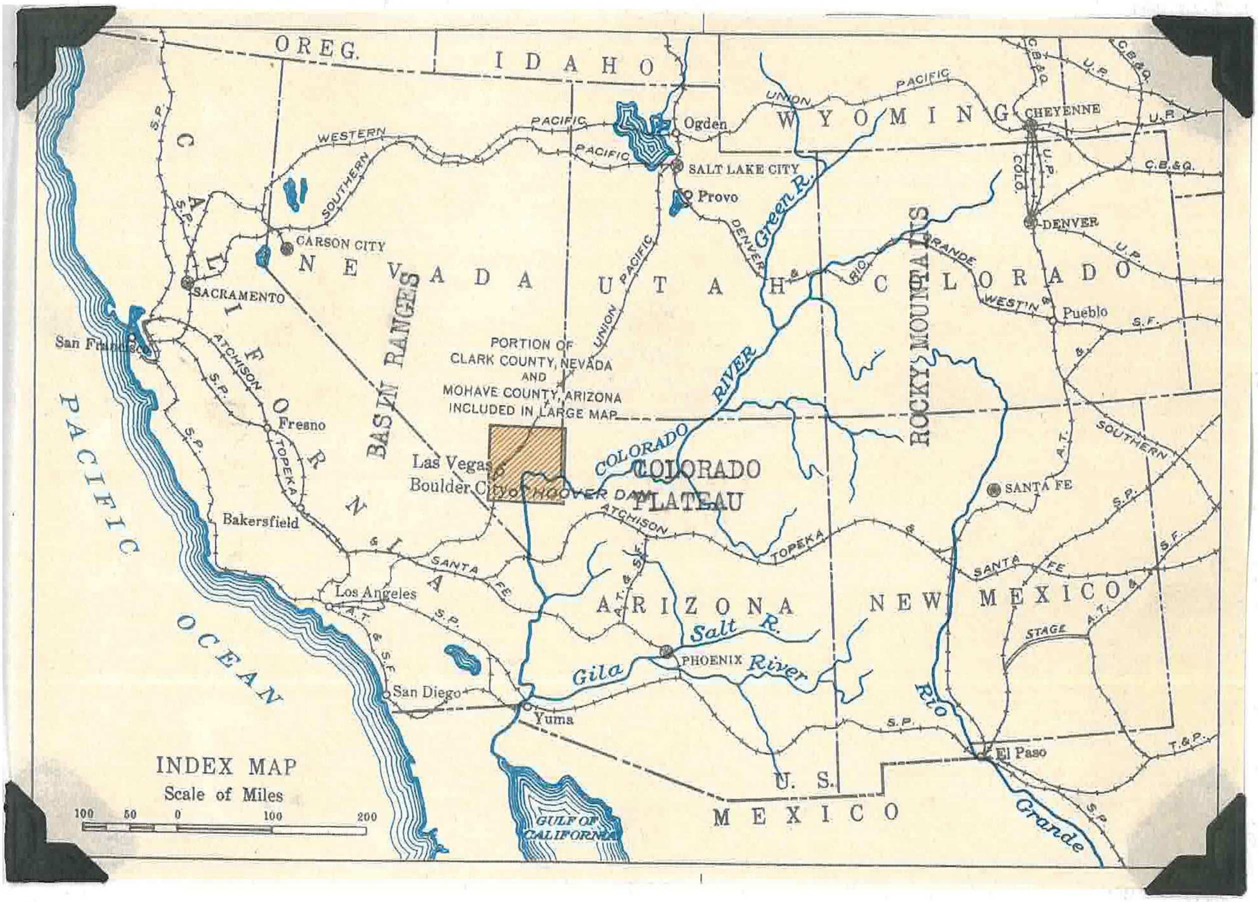

Fig. 2

MAP SHOWING RELATION OF BOULDER DAM REGION TO PHYSIOGRAPHIC PROVINCES

Showing Colorado River system. Hatched area is that covered by Bureau of Reclamation Map, No. 24,000.

elevation is approximately 3800 feet; and the summit of River Mt., situated in the hills west of Hemenway Wash, with the same approximate elevation. The lowest point is in the river bed, downstream from the dam, where the elevation of the water surface at normal stream flow is about 650 feet. The extreme local relief is thus somewhat over 3000 feet. It might here be indicated that the elevation of Boulder City is about 2500 feet, and the ultimate level of Lake Mead is 1229 feet.

The area lies within the southeastern portion of the Basin and Range physiographic province (Fig. 2). The topography of the region has been determined both by Basin and Range structure and physiography, and by the erosional processes of the Colorado River drainage. Thus, two types of topography are present in the Black Canyon region. That this is so can instantly be seen from the air, but can also be concluded by merely walking over the different parts of the area. (See frontispiece)

Most of the region back from Black Canyon and above elevation 1400 feet, although rugged, is characterized by open streamways, and can be very easily traversed on foot. In striking contrast to this is the topography of the canyon itself, and of the streamways draining into it. Cliffs and very steep slopes are the prominent features here; in fact, many parts of the canyon are inaccessible by ordinary means. Thus, Ransome (3), p. 6, concludes that "Black Canyon is a youthful topographic feature incised across a region of more mature erosional carving".

The mass of volcanic rocks in which Black Canyon has been cut is abruptly terminated about a mile north of the dam by Hemenway and Deadman Washes, which debouch upon the river from the west and east, respectively. To the north of these washes is the low country known hitherto as Callville Basin, (Longwell (4), p. 1403); when Lake Mead attains its ultimate level, this basin will be almost entirely submerged.

CLIMATE

The climate of the region is typical of the Basin and Range province, with low humidity, hot summers, and cool winters. The annual range of temperatures in Boulder City is 20° to 120° F. Most of the sparse rainfall comes in cloudbursts.

It will be interesting to note the effect, if any, of Lake Mead in increasing the humidity and moderating the temperatures of the region around Boulder Dam.

EXPOSURES

Exposures in this region are as near to being perfect as could be desired. Outcrops are not restricted by vegetation, which is very sparse, or by a covering of alluvium or mantle, which have been carried down into the lower washes. In addition, recent excavations made in connection with the construction of the dam, and cuts for roads and the railway, have offered opportunities for sampling fresh outcrops.

On the other hand, some of the contacts, as those exposed in the walls of Black Canyon, were inaccessible, due to the extreme steepness of the topography.

CONDITIONS AND METHODS OF FIELD WORK AND RESEARCH

The field work for this report was carried on from July 13 to September 23, 1937, during all but the last eight days of which the writer was under the employ of the National Park Service. The field work has consisted of collecting specimens representative of the various lithologic units, and of studying the formations as to their field characteristics, age relationships, and structural relationships.

Because of the limitation of time, and the lack of suitable base maps for detailed field mapping, this has not been attempted. A map of the generalized geology of the region has been prepared, however (Appendix).

All locating has been done on the basis of township and section corners, by means of Brunton Compass and pace. In addition, locations have been assigned to 15 minute quadrangles, in keeping with the practice of the National Park Service at Boulder City.

Mr. Ralph Klotzbier, of Company 2536, Civilian Conservation Corps, Boulder City, served as field assistant throughout the entire field period.

ACKNOWLEDGEMENTS

Many persons and organizations have given their aid in the carrying out of the field work, and in the preparation of the thesis; their cooperation is sincerely appreciated.

The National Park Service was very generous in permitting me to gather material for this thesis, while under their employ. Moreover, the Service granted the use of every facility available for carrying on the field work, including transportation, whenever possible, the use of office facilities at the Boulder City headquarters, and the use of field and mapping equipment. Except for the frontispiece, all pictures were taken by Mr. Edward T. Schenk, National Park Service geologist at Boulder City, and my immediate superior during the course of my employ, to whom I am also indebted for guidance and advice in the field.

The Civilian Conservation Corps, through the National Park Service and the United States Army, supplied the services of Mr. Klotzbier as field assistant. Meals were secured for the entire field period from the C. C. C.

The Bureau of Reclamation supplied all topographic maps available, and also gave much helpful information as to locations and elevations. Permission was granted to use the Lower Portal Road, which descends from the main highway to the river level, downstream from the power house. For the privilege of referring to Dr. Ransome's report, I am especially grateful.

Township maps were obtained from the General Land Offices in Reno, Nevada, and in Phoenix, Arizona.

Finally, I wish to offer my thanks to Dr. Ian Campbell, Associate Professor of Petrology at the California Institute of Technology, Pasadena, California, who not only was instrumental in the obtaining of the Student Technician position, but who has also given much advice and encouragement during the preparation of this thesis.

Chapter II

AREAL GEOLOGY

The rocks present in the region around Boulder Dam range in age from pre-Cambrian to Recent. Volcanic rocks predominate, but sedimentary formations and older metamorphic and plutonic rocks also occur.

PRE-CAMBRIAN ROCKS

The Black Mountain Range, which extends northward from Yucca, Arizona, to a few miles beyond Boulder Canyon, has a core of pre-Cambrian granitic and metamorphic rocks, through which a belt of Tertiary lavas has erupted. In the southern part of the range, the volcanic rocks predominate in areal distribution; but in the northern part, according to Ransome (3), p. 7, the volcanic belt has swung off to the northwest, exposing the pre-Cambrian core. The Colorado River, in crossing the northernmost portion of the Black Mountains, has cut Boulder Canyon in granitic rocks; within about 20 miles the course of the river changes abruptly from east-west to north-south, and Black Canyon has been cut through the northern portion of the volcanic belt.

At the occurrence of the Black Mountains in the area, to the east of Fortification Hill, the rocks are of the granitic variety.

Pre-Cambrian rocks also occur at the locality known as Saddle Ridge; this hill will soon become an island as Lake Mead rises to its ultimate level. The rock type here is a green chloritic schist.

PALEOZOIC AND MESOZOIC ROCKS

No rocks of undoubted Paleozoic or Mesozoic age outcrop anywhere within the area considered here. The nearest occurrence of a definitaly Paleozoic section is some 10 miles to the northwest of Las Vegas Wash.

On Water Tank Hill, an island just north of the beach at Lake Mead, Mr. E. T. Schenk has found evidences of contact metamorphism in limestone, due to intrusion by monzonite (?), with the formation of the minerals garnet and wollastonite. This limestone is possibly of Paleozoic age, but could be pre-Cambrian or Mesozoic.

LOWER OR MIDDLE TERTIARY (?) ROCKS

This group of rocks is dominant in the region around Boulder Dam; the areal extent of the formations is at least 2/3 of the total area mapped. These rocks are probably all of Tertiary age, because of their similarities to known Tertiary volcanic rocks occurring in southern Nevada and in western Arizona. It is possible, however, that the earliest formations of this group, the Altered Monzonite Porphyry (?) and the Quartz-Monzonite, are late Mesozoic in age.

Altered Monzonite Porphyry (?)

The oldest formation of this group is a series of altered igneous rocks, extending from east to west across the area, from the lower slopes of Fortification Hill to both sides of Hemenway Wash. The central portion of this belt, lying north of the head of Black Canyon, is now submerged. This same formation may extend even as far as Railroad Pass, five miles west of Boulder City. The maximum observed thickness of the formation is approximately 400 feet.

Hydrothermal alteration has in general progressed so far in these rocks that specific identification is impossible, but the original rock, as seen in the more favorable localities, seems to have been a monzonite porphyry. Possibly this formation consists of more than one kind of rock. This formation is probably lower or middle Tertiary in age, and was intruded into the pre-Tertiary rocks then present in the area. This formation is definitely older than the volcanic rocks of the region.

Quartz-Monzonite

The hills southeast of Hemenway Wash extending from Boulder City towards Black Canyon consist mainly of quartz-monzonite. This monzonite differs from the variety described above in being much less altered, and in having an equi-granular texture. Tank Hill, at Boulder City, presents outcrops of very fresh Quartz-Monzonite. The maximum observed thickness of this formation is 300-400 feet.

It is believed that the Quartz-Monzonite is intrusive into the Altered Monzonite Porphyry (?). There are localities, east of Hemenway Wash, where the contact between these two formations is sharp, rather than gradational, indicating that they are separate units.

Older Volcanic Series

The oldest volcanic formation in the area is the group of rocks here called the Older Volcanic Series. This is the most abundant formation in areal extent, and occurs for the most part on the Nevada side of Black Canyon. It is at least 1500-2000 feet thick, and may be considerably thicker, as the base of this formation was not exposed in the area.

This series, consisting mainly of andesite flows, but containing some sedimentary breccia members, makes up the bulk of the hills northwest of Hemenway Wash. To the southwest of the prominent fault, situated due northwest of Boulder City, the upfaulted Altered Monzonite Porphyry (?) succeeds the Older Volcanic Series. The topographic expression of this fault is a very deep canyon, here designated as "Fault Canyon". (Fig. 3). The contrast in color between the red Altered Monzonite Porphyry (?) and the

Fig. 3

"FAULT" CANYON

Taken looking northwest from Boulder City. Altered Monzonite Porphyry (?) on left is reddish in color, while Older Volcanic Series on right is brown to black. (N. P. S. No. 1016).

Fig. 4

RELATIONS BETWEEN OLDER VOLCANIC SERIES AND QUARTZ-MONZONITE

Taken on Edison power line road, 1 mile south of Hemenway Wash, looking west. Ridge marked with x shows horizontal attitude of lavas, while higher ridges to left are of massive quartz-monzonite. (N. P. S. No. 1027).

black to brown Older Volcanic Series is very striking.

This formation is present also in the hills southeast of Hemenway Wash, especially in the section midway between Boulder City and Boulder Dam. The attitude of the Older Volcanic Series lavas is nearly horizontal here. (Fig. 4). The lower contact of the lavas is not exposed, but the upper boundary is practically a horizontal plane. In these hills, the Older Volcanic Series occurs below this level, while the Quartz-Monzonite occurs above. Moreover, the lavas do not show any deformation where they are in contact with the Quartz-Monzonite, which they should if intruded by the latter. Hence it is concluded that the Older Volcanic Series is younger than the Quartz-Monzonite, having erupted through it.

About 1/2 mile downstream from the dam, in Black Canyon, the Older Volcanic Series emerges from beneath the Dam Breccia and Younger Volcanic Series, and has a steeper dip than the latter. (Fig. 18, p. 75). Thus there was a period of faulting and tilting before the deposition of the younger formations.

Dam Breccia

In Black Canyon and upon the Older Volcanic Series lies the sedimentary formation, Dam Breccia. The contact between it and the Older Volcanic Series was not clearly exposed, but probably it is an unconformable one, since the Older Volcanic Series has in general a steeper dip. Although it is possible that the Dam Breccia belongs with the Older Volcanic Series structurally, it has been considered a separate formation because of the limitation of its exposure to Black Canyon, and its differences in lithology.

The Dam Breccia occurs in the lower portions of the walls of Black Canyon, for about 2000 feet upstream and downstream from Boulder Dam. It is somewhat lens shaped, attaining a maximum thickness of about 350 feet near the dam, and thinning out to the northeast and the southwest.

Younger Volcanic Series

Unconformably upon the Dam Breccia and Older Volcanic Series has been deposited the group of volcanic and sedimentary rocks designated as the Younger Volcanic Series. All the members of this series occur in the walls of Black Canyon or adjacent thereto. There is a pronounced unconformity shown between the oldest member of this formation, the Latite Flow-Breccia, and the underlying Dam Breccia; this feature is displayed in the walls of Black Canyon, downstream from the dam.

The Latite Flow-Breccia, consisting of one or more flows, comprises the upper portion of the canyon walls, and extends for at least 1/2 mile to the west, and somewhat less to the east. Just east of Observation Point, this formation is shown to be in fault contact with the Older Volcanic Series. (Fig. 5). The thickness of the Latite Flow-Breccia is at least 800-1000 feet.

Above the Latite Flow-Breccia is a sedimentary formation, Spillway Breccia. It occurs mainly at the site of the Arizona spillway, but is present on both sides of the canyon. It is a very coarse and variable breccia, and is 200-300 feet thick. Fig. 6 shows the Spillway Breccia lying in a basin in Latite Flow-Breccia.

The Augite Latite lies above the Spillway Breccia, and is extensive on both sides of the river. It is especially prominent on the Nevada side, north of the dam, where it typically forms cliffs. This formation consists of one or more flows, and is 150-200 feet or more in thickness.

Next in the series is the Sugarloaf Tuff. It is localized in extent, being found only on the Arizona side of Black Canyon. It is most prominent

Fig. 5

FAULT CONTACT BETWEEN OLDER VOLCANIC SERIES AND LATITE FLOW-BRECCIA

In railroad cut, just east of Observation Point; looking north. Much breccia in fault zone. (N. P. S. No. 1025).

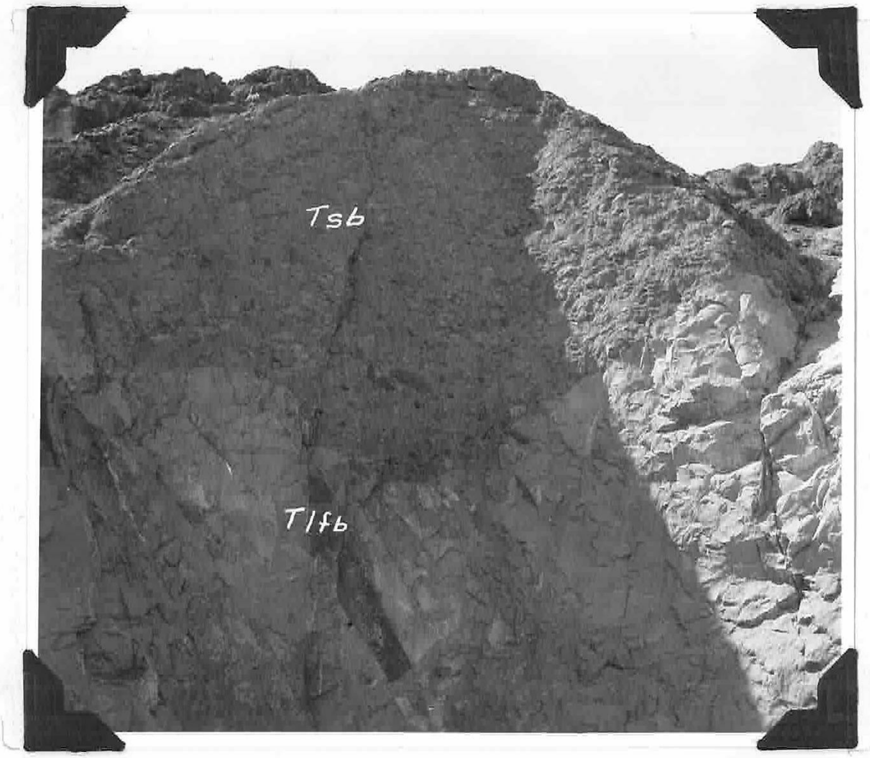

Fig. 6

CONTACT BETWEEN SPILLWAY BRECCIA AND LATITE FLOW-BRECCIA

Above south end of Arizona spillway. (N. P. S. No. 1018).

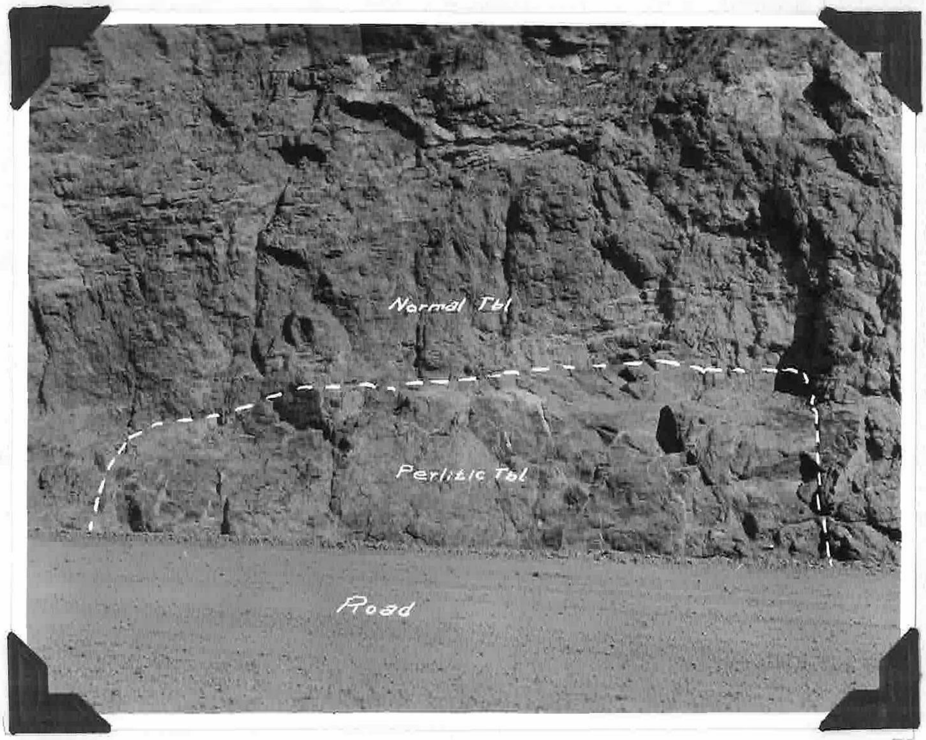

Fig. 7

CONTACT BETWEEN PERLITE AND NORMAL BIOTITE LATITE

Along main highway, in Arizona, about 1/2 mile along highway from Boulder Dam. (N. P. S. No. 1024).

at Sugarloaf Hill, just south of the dam. Its maximum thickness is about 200 feet, but 75 feet is the usual figure. The Sugarloaf Tuff overlies Augite Latite and underlies Biotite Latite, to which it is related petrographically.

The Biotite Latite is the most extensive of the Younger Volcanic Series lavas. It consists of one or more, probably many, lava flows. Its maximum thickness is about 400 feet, almost all of it being more than 200 feet thick. The basal flow is often a black perlitic variety. (Fig. 7). The Biotite Latite extends for 1/2 mile east and west of Black Canyon, and extends southward beyond the area here considered.

Biotite Latite occurs in one puzzling area, situated in the hills west of Hemenway Wash, just west of Bootleg Canyon. Here a rock mass, at least 1/8 mile on a side, has apparently been downfaulted against Older Volcanic Series. A very striking fault exposure is seen in a prospect cut in Bootleg Canyon, and shows the relations of these two formations; dragging and a 20 inch fault zone filled with manganiferous material are featured. (Fig. 8). The rocks from the two localities appear the same petrologically, both in hand specimen and in thin section. Moreover, both carry secondary quartz, as veins or amygdule fillings; such secondary mineralization has not been observed in any other volcanic rock in the area. Inasmuch as no Biotite Latite, either in outcrop or in float has been noticed between the Bootleg Canyon locality and the most westerly occurrence of the Black Canyon Biotite Latite, near the upper terminus of the Lower Portal Road, a straight line distance of at least 5 miles, it is suggested that the eruption of Biotite Latite may have occurred from at least two different volcanic centers.

The Chlorophaeite Tuff was found at only one locality in the area, 300 yards west of the main highway, in Arizona, and opposite the turnoff

Fig. 8

FAULT CONTACT BETWEEN OLDER VOLCANIC SERIES AND BIOTITE LATITE

In Bootleg Canyon, 1/8 mile south of summit; looking west. Dragging is indicated in the Older Volcanic Series. 20 inch fault zone filled with manganiferous material. (N. P. S. No. 1019).

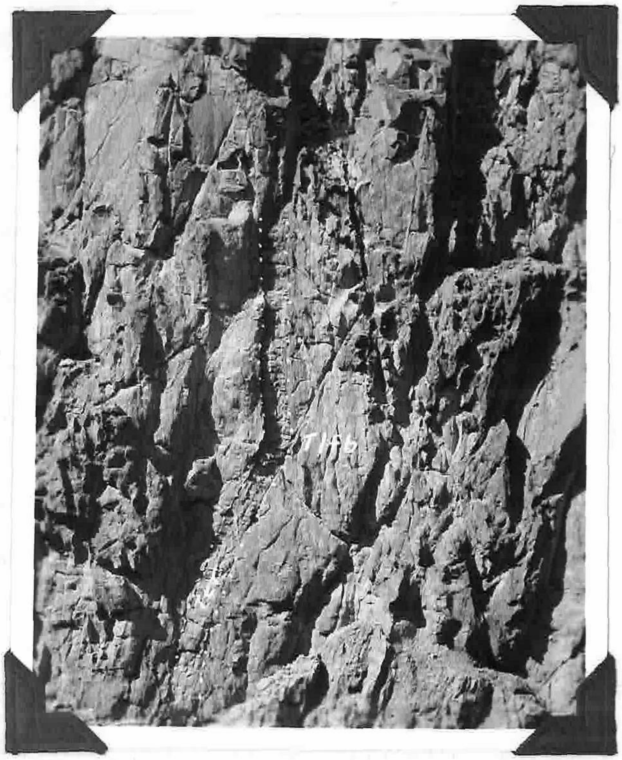

Fig. 9

DIKE OF TRACHYDOLERITE IN LATITE FLOW-BRECCIA

In the canyon followed by the Lower Portal Road; near the river level. The dike is controlled by jointing in the flow-breccia. (N. P. S. No. 1022).

of the road to the base of Fortification Hill. Here 10-15 feet of the formation are exposed in a small gully. The Chlorophaeite Tuff here overlies Biotite Latite, and is younger than at least part of that formation. No rocks lie above the tuff, and hence it could not be determined whether it was younger than all of the Biotite Latite.

Younger than the Biotite Latite is the formation designated as Trachydolerite. The field name for this rock might be basalt, but thin section study shows the former designation more apt. This formation is typically intrusive into the older formations, but it may have poured out as lava flows in places. Its occurrence is mainly in and near Black Canyon; it is especially prominent in the canyon walls, where it occurs as dikes and sills. (Fig. 9). The maximum thickness of the Trachydolerite is about 50 feet, where it occurs as sills.

The youngest member of the Younger Volcanic Series is the sedimentary formation, Dry Camp Breccia. This formation, exceedingly well sorted and stratified, and up to 300-400 feet in thickness, has fragments of both trachydolerite and granitic rocks, though not usually together. The breccia occurs entirely on the Arizona side of Black Canyon, and extends northward from about 1/2 mile east of the dam. (Fig. 10).

The Dry Camp Breccia has pronounced angular unconformity with the underlying Biotite Latite, and hence there was probably a period of tilting and erosion involved. It is not thought that this period was so long as to make this formation as young as the Muddy Creek Formation, which underlies Fortification Hill, about 3 miles to the north.

The presence of many fragments of trachydolerite in the breccia, and the unconformity with the Biotite Latite, are the main reasons for placing the Dry Camp Breccia above the Trachydolerite in the stratigraphic column.

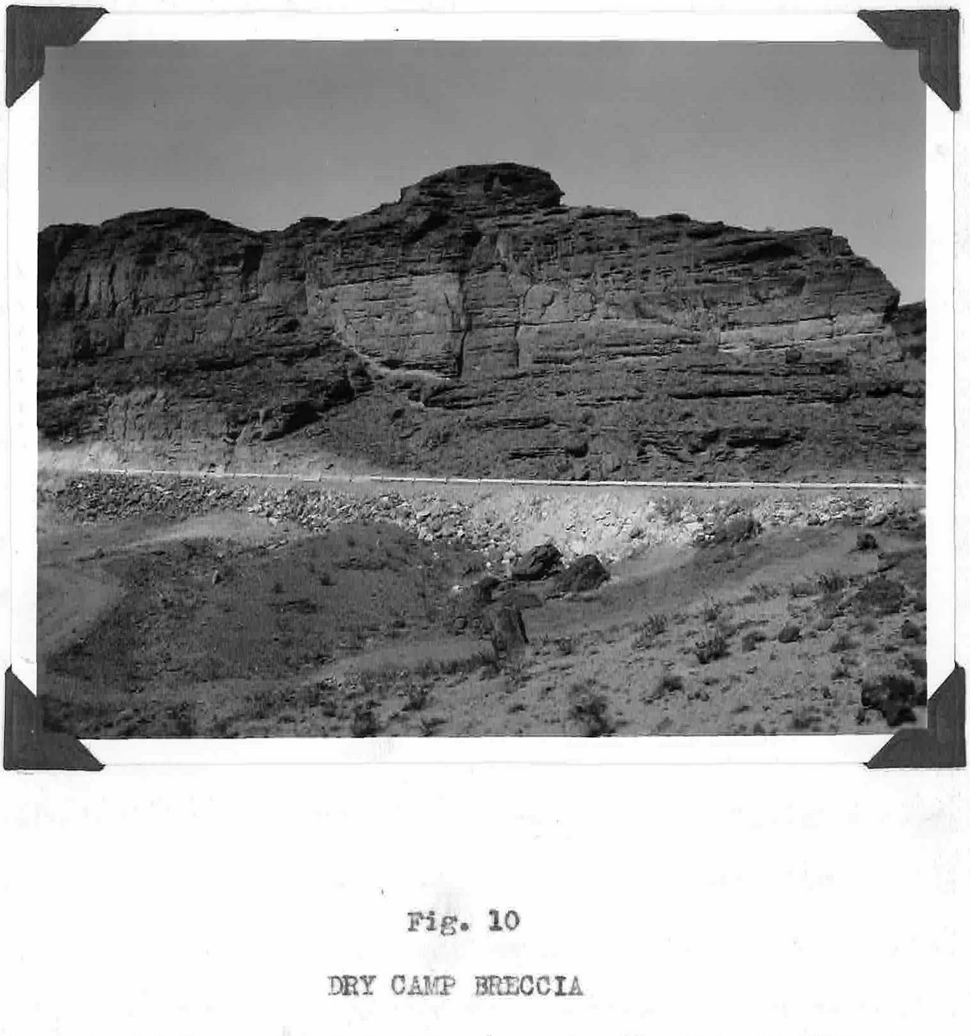

Fig. 10

DRY CAMP BRECCIA

Taken along main highway, in Arizona, about 1 mile from Boulder Dam. Breccia is well sorted. Lower contact, with Biotite Latite, at left. (N. P. S. No. 1021).

The pronounced unconformity with the Biotite Latite suggests that the breccia is quite young, compared to the other members of the Younger Volcanic Series. Further to the east a basalt flow has been found on top of the breccia; whether this is Trachydolerite was not proved. It is possible that the Trachydolerite is in part older, and in part younger than the Dry Camp Breccia.

It must be here stated and emphasized that the chronological sequence presented for the members of the Younger Volcanic Series is at best only a general one, covering the majority of apparent age relationships. Many formations interfinger to some extent with the younger and older members. The Biotite Latite and the Spillway Breccia were especially puzzling in this regard. Apparently the periods of eruption and sedimentation were to some degree contemporaneous or overlapping.

LOWER PLIOCENE (?) ROCKS

The occurrences of lower Pliocene (?) rocks in the area are limited to the northeast part, at and near Fortification Hill.

Muddy Creek Formation

A sedimentary formation, part of the elsewhere extensive Muddy Creek Formation, occurs under the lava capping of Fortification Hill. Longwell (4), Plate 2, has correlated the fanglomerates of Fortification Hill with the Muddy Creek Formation of the Virgin River region. The fragments in this formation, as determined from the few places accessible, were of granitic rocks. The observed thickness was about 500 feet, but may be greater. Stock (5) has dated this formation as Lower Pliocene (?).

Fortification Hill Basalt

Conformably, and apparently of the same age as the fanglomerates, the

Fig. 11

FORTIFICATION HILL

Looking north from road to base of hill. "Devil's Paintbox" in middle distance. (N. P. S. No. 1020).

Fortification Hill Basalt overlies the Muddy Creek Formation. (Fig. 11). About 40 separate flows make up the thickness of about 400 feet. Due to the very slight lateral variation in the thicknesses of individual flows, it is probable that these flows once covered a much larger area than is represented by this remnant.

The age of lower Pliocene (?) assigned to these formations must be the lower limit. The basalt and the fanglomerates cannot be very old because of their topographic situation, with respect to the Colorado River, some 3000 feet lower, (before the impounding of Lake Mead). They could not have lain in their present position for a great length of time without being completely removed by erosion. Moreover, the lavas rest directly on the granitic rocks of the Black Mountains at their eastern margin, and hence were probably erupted after the last uplift of the range. It is possible that these formations are very much younger than lower Pliocene (?), and they may be even of Pleistocene age.

QUATERNARY DEPOSITS

Quaternary deposits in the area include terrace gravels, deposited by the Colorado River during its course of cutting Black Canyon, and alluvium, still being deposited. Basaltic lavas lie upon gravels some eight to ten miles south of Boulder Dam, and east of the Colorado River. These lavas are Pleistocene or Recent in age.

Chapter III

PETROLOGY AND PETROGRAPHY

In this chapter it is proposed to discuss those formations, established in the preceding chapter, which have been studied petrologically, as regards their petrographic and petrogenic features.

ALTERED MONZONITE PORPHYRY (?)

The Altered Monzonite Porphyry (?) is more important petrologically as regards the alteration which it has undergone, than in connection with the primary character of the rock. This alteration has given rise to the formation of alum and alunite, which minerals are elsewhere of economic importance, when in sufficient concentrations. The alunite and gold deposits of the Railroad Pass district, situated some five miles west of Boulder City, for example, owe their origin to this same type of rock alteration. This locality is discussed in (6), pp. 54 and 144-145.

The most striking feature of this rock is its intense coloration. Brilliant reds and whites are the usual colors. Along the base of Fortification Hill, where the alteration seems to have been the most intense, the red coloring has earned for this locality the name of "Devil's Paintbox". (Fig. 11). The color of the Altered Monzonite Porphyry (?) ranges in various parts of the area from nearly all red to nearly all white, according to the proportion of iron oxides present. In hand specimen this rock shows dead white fragments, ranging up to 1 inch in size, embedded in a red, fine grained matrix. This is suggestive of either a very porphyritic rock, or of a coarse breccia. At one locality, in Bootleg Canyon, the white areas were found to be arranged in parallel rows.

In thin section the rock consists dominantly of secondary minerals, including hematite, sericite, kaolinite, and alunite. The matrix comprises from 2/3 to 3/4 of the section, and is dominantly of sericite and hematite; the red color of the rock is due to the latter. Disseminated through this matrix are small grains of pyrite, which have not yet been converted to iron oxides. The remainder of the section consists of fragments of what appears to be a monzonite porphyry. These fragments have a groundmass altered to sericite and kaolinite, with some alunite; while the phenocrysts, which are often large, are partially replaced by sericite and kaolinite. They are dominantly of medium plagioclase, and show a general alignment, suggesting a possible volcanic or hypabyssal mode of formation. A lesser number of mafic phenocrysts are present, but these have been entirely converted to hematite and other secondary minerals.

Many small veinlets and pockets of gypsum traverse the section. The formation of this mineral is probably related to the metasomatic processes which have affected this rock.

Because of the uncertainty of the determination of the primary rock type, and the possibility that more than one rock type occurs within the formation, it has been named Altered Monzonite Porphyry with a query.

The pyrite doubtless is the source for the alteration agents. It was disseminated throughout the rock, possibly associated with the extrusion of the younger lavas of the area. The pyrite was subsequently oxidized to sulfuric acid, which converted the primary rock minerals to secondary iron oxides, kaolinite, sericite, alunite, etc.

Intensive as the alteration of the Altered Monzonite Porphyry (?) described above has been, there are two localities within the area where the process has been carried to its ultimate extreme. These two localities are situated at the mouth of Bootleg Canyon, in the east central portion of

Sec. 6, T 23 S, R 64 E, Nevada; and 1/4 mile east of the junction of the beach cutoff with the main highway, in the southwest 1/4 of the southwest 1/4 of Sec. 25, T 22 S, R 64 E, Nevada.

This further alteration has changed the red color to yellow. On an exposed surface, the rock appears crumbly and ashey, resembling a tuff. The rock which has not undergone surface weathering is grey-white in color, rather massive in texture, and crossed by many veins of limonitic appearing material, and also by gypsum. The rock apparently contains abundant alunite.

The thin section of this rock shows a fine grained texture with a mineralogy entirely secondary. Here the phenocrysts, which are scarcely distinguishable from the groundmass, consist dominantly of sericite, but with some kaolinite and alunite; no trace of the original plagioclase remains. The groundmass consists of alunite, sericite, and gypsum, with lesser amounts of jarosite and limonite. Veinlets and spherical masses of gypsum occur throughout the section.

Especially interesting are the veinlets and crystals of jarosite, which occur in the section, associated with the alunite. The mineral is a deep yellow in color, and very refringent and birefringent. The individual crystals are usually well formed rhombs. All the iron present as hematite in the red rock, described above, has apparently gone into the jarosite, during this hydrothermal alteration. The relations between the gypsum veinlets and the jarosite veinlets show that the former were formed last, since they offset the jarosite veinlets in many instances.

Scattered throughout this rock are numerous grains of pyrite, in far greater proportion than in the reddish rock; many of these grains are euhedral. The abundance and the euhedral nature of these pyrite grains indicate that they are probably due to a second period of mineralization, subsequent to the alteration from the oxidation of the first stage.

As explained in the chapter on mineralogy and economic geology, concentrations of gypsum and alum accompany these rocks, at the two localities described above.

QUARTZ-MONZONITE

Except for the Altered Monzonite Porphyry (?), which is generally so intensely altered that the nature of the original rock is beyond discernment, and the pre-Cambrian granitic rocks and schist, which have been considered in this paper only as regards their structural relationships, the Quartz-Monzonite is the only plutonic rock in the area; the remainder are either volcanic or sedimentary in origin. In many respects this rock has been the most favorable one in the entire area for petrographic study.

Megascopically, the rock is grey in color, and consists mainly of grey to colorless feldspars with a lesser proportion of green hornblende. A few flakes of biotite are visible. The texture is of fine to medium granularity, while the minerals are very even granular. None of the minerals show any conspicuous orientation, and none of the quartz is visible in hand specimen.

When exposed to the elements, the surface of this rock assumes a chalky, white appearance, probably due to the kaolinization of the feldspars. The dark minerals are altered to brown iron oxides. When intense weathering has affected the surface, it becomes somewhat pock-marked in appearance, due to the removal of certain feldspar grains, while leaving others intact.

In thin section the rock is dominantly felsic, with plagioclase and orthoclase the main constituents, along with quartz. The mafic constituents are green hornblende, biotite, and magnetite. The following Rosiwal analysis, made with the integrating stage, gives the percentages by volume of the main minerals:

Plagioclase	36%	Hornblende	12%	Magnetite	2%
Orthoclase	35	Biotite	5	Apatite	present
Quartz	10				

The order of crystallization of these minerals is: apatite, magnetite, hornblende, biotite, plagioclase, orthoclase, and quartz.

Apatite is present as thin laths, and as plates. It is usually found in the biotite, but occurs in all other minerals, towards which it is euhedral.

The magnetite occurs as small equant grains, which are generally subhedral, but in a few cases crystallized as cubes. It often carries inclusions of apatite, and is usually associated with the biotite or hornblende.

The hornblende occurs in slightly elongated forms, and in both basal and prismatic sections. It is pleochroic in shades of green. The maximum extinction angle in prismatic section is about 15°.

The biotite is brown, very pleochroic, and shows excellent birds-eye maple texture. It occurs as elongated plates and as basal sections. Numerous inclusions of the earlier minerals occur in the biotite.

The plagioclase, as determined from both albite and albite-Carlsbad twinning extinction angles, is labradorite of composition An_{53}. This seems rather calcic for a quartz-monzonite, but accounts for the subhedral to euhedral habit of the plagioclase laths in thin section. The laths are often quite large, and are invariably surrounded by subhedral to anhedral, later crystallizing orthoclase. Basal sections of the plagioclase often show marked zoning. The albite twinning lamellae are often quite broad, and many Carlsbad twins occur.

The orthoclase is arranged with respect to the plagioclase in a typical monzonitic texture. The late crystallizing orthoclase is anhedral to, and often completely surrounds, the euhedral to subhedral plagioclase. Occasionally the two feldspars have the same crystallographic orientation.

The quartz is the last of the minerals to crystallize, and is anhedral towards all other minerals, usually filling their interstices. It contains less inclusions than the other minerals, and is notably unstrained.

The specimen from which the thin section was made was collected from the top of Tank Hill, Boulder City. This outcrop presents one of the freshest exposures obtainable of the formation, because of the recency of the excavations there. Consequently, the thin section shows very little alteration. The only appreciable effect is kaolinization, accompanied by slight sericitization, on the orthoclase. The other minerals are quite fresh. This kaolinization of the orthoclase has proved a very simple means of differentiating it from the plagioclase, which is practically unaltered.

The percentage of quartz in the rock is high enough to place it in the Quartz-Monzonite category, with the equal amounts of the two feldspars present. This corresponds to Johannsen's type adamellite.

OLDER VOLCANIC SERIES

The Older Volcanic Series consists of a succession of andesite flows and sedimentary breccias; of these the volcanic rocks are by far the more abundant. The lithologic character of this formation is about the same at all of its major occurrences within the area. The petrographic features of the more common type of this rock, as demonstrated by specimens from three localities, will be discussed first; then will be described the features of special types of this series, which occur only at a few places within the area.

The most abundant variety of the Older Volcanic Series is a rock, grey-brown to brown in color, fine grained in texture, and carrying phenocrysts of white plagioclase in greater or lesser amounts. In some localities, as in Bootleg Canyon, the phenocrysts are very pronounced; in others, as near Observation Point and in Black Canyon, below the dam, they are scarcely visible. In the main variety of the formation no phenocrysts of dark minerals are visible megascopically; they are either present in only small amounts, or have been completely repleced by secondary minerals.

In thin section the most prominent feature of this rock is the presence of abundant plagioclase phenocrysts in a very fine grained groundmass. These phenocrysts attain their greatest size and abundance at the Bootleg Canyon and Black Canyon localities. Here they are up to 3 mm. in size, and comprise from 15 to 30% of the section. At Observation Point they are less than 1 mm. in size, and make up only 5 to 8% of the section. In all cases the phenocrysts are sub-equant to somewhat elongated, subhedral to euhedral, and with no apparent orientation.

The composition of the plagioclase, as determined from albite twinning extinction angles, is labradorite of composition ranging from An_{50} to An_{54}, in the different specimens. This is quite a small range considering the distances between the various localities.

In the Bootleg Canyon rock, no phenocrysts other than plagioclase are present. The rock contains about 2% magnetite in large masses, most, if not all, of which is secondary. Much of it shows the six-sided outline of hornblende crystals, and in places traces of the original hornblende still remain. In the Black Canyon rock less magnetite is present, and many euhedral hornblende crystals are present, which have been replaced by magnetite and other minerals to varying degrees. The Observation Point rock has about 5% magnetite, mostly in small masses, and only a very few hornblende crystals remain unaltered.

In each of these rocks the groundmass consists of a devitrified glass, brown in color, and with some laths of feldspar. The index of refraction of this groundmass is approximately that of the balsam, 1.54. Comparing with the data of W. O. George (11) this corresponds most nearly to an andesite.

The alteration of this rock is generally only moderate. The dark minerals are usually replaced by iron oxides, mainly magnetite. The plagioclase phenocrysts are replaced by calcite and sericite to varying degrees. The alteration is just incipient at the Bootleg Canyon locality, moderate at Black Canyon, and almost complete at Observation Point. The groundmass is partially altered to kaolinite, sericite, and calcite. In the Observation Point rock, many veins of calcite traverse it. In thin section these veinlets are seen to completely replace plagioclase phenocrysts where they lie across their paths; the twinning lamellae of the plagioclase are still discernable, but the crystal is entirely of calcite.

As indicated in earlier chapters, this formation is quite extensive both in areal distribution and in stratigraphic thickness; it is approximately as thick as the Younger Volcanic Series, which consists of 8 different formations. For this reason it seems desirable to call this formation a Series, rather than to restrict it by a petrographic designation. TheyYounger and Older Volcanic Series are separate from each other structurally as well as petrologically, and, as explained in the chapter on structure, there is a time gap between the deposition of these two formations.

In the canyon which strikes off northwest from Bootleg Canyon, about 1/4 mile below its summit, and just west of Bootleg Canyon, occurs a small mass of a green rock, which belongs to the Older Volcanic Series. This mass is in a knife edge contact with the main variety of the formation, described above, and seems to be older than it. The evidence for this is the numerous inclusions of the green rock occurring in the brown variety adjacent to the contact. This contact is so sharp that it has been possible to make a thin section across it, showing both rocks. Because of the limitation of the exposure, the structural relationships of these two rocks has not been solved. Possibly the relation is an older flow of the green rock cut by a near surface dike or sill of the brown, which connects with the flows above.

This rock is greyish green in color and contains numerous needles of hornblende, up to 1 cm. in length, in a fine grained groundmass. There is no orientation of the phenocrysts.

In thin section the rock consists of large phenocrysts of basaltic hornblende in a very highly altered groundmass. The basaltic hornblende is pleochroic in shades of yellow to brown, is length slow, has high relief and birefringence, and has a maximum extinction angle of about 10°. The crystals have borders of hematite and magnetite, which also traverse the cleavage cracks of the hornblende. In addition, a smaller number of plagioclase phenocrysts, probably labradorite, occur in the rock; these are not nearly so large as the hornblende crystals.

The groundmass is holocrystalline and consists mainly of feldspar laths, largely altered to calcite and sericite. Also much serpentine is present in the section, pseudomorphic after the basaltic hornblende and possibly other dark minerals. Much magnetite is present, in addition to that associated with the hornblende.

The presence of basaltic hornblende might possibly be due to the oxidation of the iron of original hornblende during the intrusion and extrusion of the main variety of the Older Volcanic Series; more likely, however, the basaltic hornblende was formed during the period of formation of the green rock. Andesites are a common home for basaltic hornblende, which forms late in the magmatic stage due to oxidation of the iron by hot gases, etc. This rock has the petrographic designation of a hornblende andesite.

On the crest of the hills west of Hemenway Wash, and above the barite-turquoise locality at Apache Claim No. 4, occurs an andesitic member of the Older Volcanic Series, different from the usual type. The rock here weathers the same as the main type, but the fresh surface is bluish grey in color, and shows abundant white phenocrysts of plagioclase, often ranging up to 2 mm. in size. A few dark minerals are seen, but these are completely replaced.

In thin section the outstanding feature of this rock is the intensity of the alteration. Practically the entire section consists of calcite, sericite, and kaolinite. Many large euhedral phenocrysts of calcite, kaolinite, and sericite, but with the crystal form of plagioclase occur. Both the twinning lamellae and the cleavage are preserved in these pseudomorphs; the plagioclase corresponds to labradorite in composition. The groundmass of the rock consists of a fine grained mixture of calcite, sericite, and magnetite. Any dark minerals originally present as phenocrysts have been replaced by magnetite. Many calcite veinlets traverse the section.

The last special rock type of the Older Volcanic Series to be considered is a sedimentary breccia member, occurring about 30 feet below the summit, just north of the Bootleg Canyon locality described above. Here is a sedimentary breccia series, about 50 feet thick, resting with slight unconformity upon the normal andesite of the Older Volcanic Series. The weathering of this breccia has produced many cavities parallel to the stratification; many of these are up to 1 foot in size. This breccia is fairly well sorted and well stratified.

The hand specimen of this rock shows a hard, well cemented breccia, reddish grey in color, consisting of sub-angular fragments of the red Altered Monzonite Porphyry (?) and other rock types in a somewhat porous matrix, grey in color. The fragments are rather uniform in size, and range up to 1 cm., though most are 2-3 mm. The bedding is discernable in the hand specimen by the alignment of the small pits.

The thin section of the breccia shows angular to sub-angular fragments of various rock types embedded in a matrix which is mainly silicic. The fragments consist of Altered Monzonite Porphyry (?), Quartz-Monzonite, and andesite of the Older Volcanic Series. Many crystals of plagioclase, biotite, and magnetite are present, and range in particle size down to that of the matrix. The main portion of the matrix consists of small sub-angular grains of quartz and feldspar, with small proportions of other minerals. Alteration of this rock, beyond that characteristic of the rocks present as fragments, consists mainly of additional replacement by sericite and calcite.

It may appear from the above description of the various rocks present in the Older Volcanic Series that the formation might be subdivided into various volcanic and sedimentary formations. This has not been done because, (1) the brown andesitic type, described first, is by far the most extensive rock type, almost to the exclusion of the others, and (2) not enough field work has been done to obtain the lithological and structural data necessary for such a subdivision. More field work in the future, carried out in more detail, and over a larger area than that covered here, may show that such a subdivision is practicable.

DAM BRECCIA

The Dam Breccia is a sedimentary deposit, and is quite variable in composition. It consists of fragments, mainly of Quartz-Monzonite, but with some of Altered Monzonite Porphyry (?), Older Volcanic Series, and other volcanic rocks, in a reddish-brown matrix consisting of iron oxides and silica. This formation is quite variable in coarseness, the size of the fragments ranging down from 1 foot to that of the matrix particles. The finer grained members of this formation, especially the reddish sandstone members, have pronounced bedding, which is indicated by the alignment of weathering cavities; this feature is visible in the lower parts of Black Canyon, near the dam.

Because of the coarseness of most of this breccia, the specimen for thin section study was taken from a reddish volcanic sandstone member, occurring in the walls of Black Canyon, near the Nevada lower portal #1. The hand specimen shows a hard, fine grained, red sandstone, uniform in texture, and well bedded, as seen from the alignment of the light colored minerals.

The thin section shows many of the same features visible in hand specimen. Sub-angular fragments of different kinds of rocks are embedded in a fine grained matrix. The fragments include the rocks mentioned above, and also detrital grains of quartz, feldspar, biotite, and hornblende. The groundmass is highly ferriferous, containing abundant hematite and magnetite, along with the siliceous minerals. Many of the fragments show stress effects, such as granulation of quartz, bending of biotite flakes, etc. Sericite, calcite, and kaolinite are the common alteration products of the felsic minerals of the breccia.

Because of the variation in composition of different members of this formation, no petrographic name seems applicable to the whole formation. Ransome (3), p. 18, has named it the Dam Breccia, on account of its occurrence at the dam site, and this designation will be retained in the present paper.

YOUNGER VOLCANIC SERIES

The Younger Volcanic Series has been divided into 8 volcanic and sedimentary formations, each of which has its own lithologic and petrographic characteristics, and which will be described separately, in chronological order.

Ransome (3), pp. 9-42, has studied that part of the series immediately adjacent to Boulder Dam, and certain of the field data given for the members of this series are due to him.

Latite Flow-Breccia

The Latite Flow-Breccia is one of the most distinctive rocks in the area. The rock consists of small, brownish, angular fragments of latite embedded in a streaky light brown matrix. The streakiness is a flow structure, due to the congealing of the lava while in motion. The fragments show assimilation and digestion to varying degrees. Around the borders of these partly assimilated fragments often appears a zone of yellow iron oxides, probably due to oxidation of the iron during the process. The fragment size varies from 1 inch on down; also, the abundance of the fragments varies at different localities, being almost absent at some.

Very few phenocrysts are visible in the hand specimen of the rock; a few small biotite flakes and white plagioclase crystals are visible. Those latite fragments which are elongated tend to align with the flow structure.

In thin section, also, the presence of fragments of the same composition as the matrix is the dominant feature. The fragments merge into the matrix at times so imperceptibly that they can scarcely be distinguished from it; the main difference is the presence of more magnetite and hematite in the fragments. Many biotite phenocrysts are present in the rock; these are very pleochroic in shades of golden brown to straw yellow. Any other mafic phenocrysts have been replaced by iron oxides. Plagioclase phenocrysts are also abundant; they are embayed by the groundmass, more so than the biotite. Their composition is sodic andesine. Smaller phenocrysts of orthoclase occur; these grade in size down to the grain size of the groundmass.

The hypohyaline groundmass is a partly devitrified glass, light brown in color, and with an index of refraction below balsam. Most of the groundmass feldspar is orthoclase.

This rock is a latite in composition, since both feldspars are present. Its mode of origin is brecciation and assimilation of latite by lava flows of approximately the same composition, producing a flow-breccia. The petrographic designation of this rock is hence Latite Flow-Breccia.

Spillway Breccia

The Spillway Breccia is an intervolcanic sedimentary formation, overlying Latite Flow-Breccia and usually underlying Augite Latite and Biotite Latite. This formation is very variable as regards size of fragments and degree of rounding. The greater part of it consists of coarse, poorly assorted material, as at the Arizona spillway. (Fig. 6, p. 21). These fragments often occur as large as 6 feet in diameter. Fig. 12 shows such a boulder of glassy latite in the Spillway Breccia. This latite may be the same as the perlitic facies of the Biotite Latite; if this be so, the deposition of the Spillway Breccia and the eruption of the Biotite Latite must have been to some extent contemporaneous or overlapping. The coarser variety of the Spillway Breccia, whose fragments vary in degree of rounding from angular to sub-rounded, grades laterally and vertically into well bedded grits and flaggy sandstones. These finer, well bedded, varieties of the formation generally occur as lenses in the coarser variety.

The flaggy sandstone and grit were the most practicable varieties for thin section study, because of their small grain size. Both are light grey in color, and even granular. The sandstone is very finely bedded, and cleaves easily parallel to this bedding; the grit is coarser, the particle size being

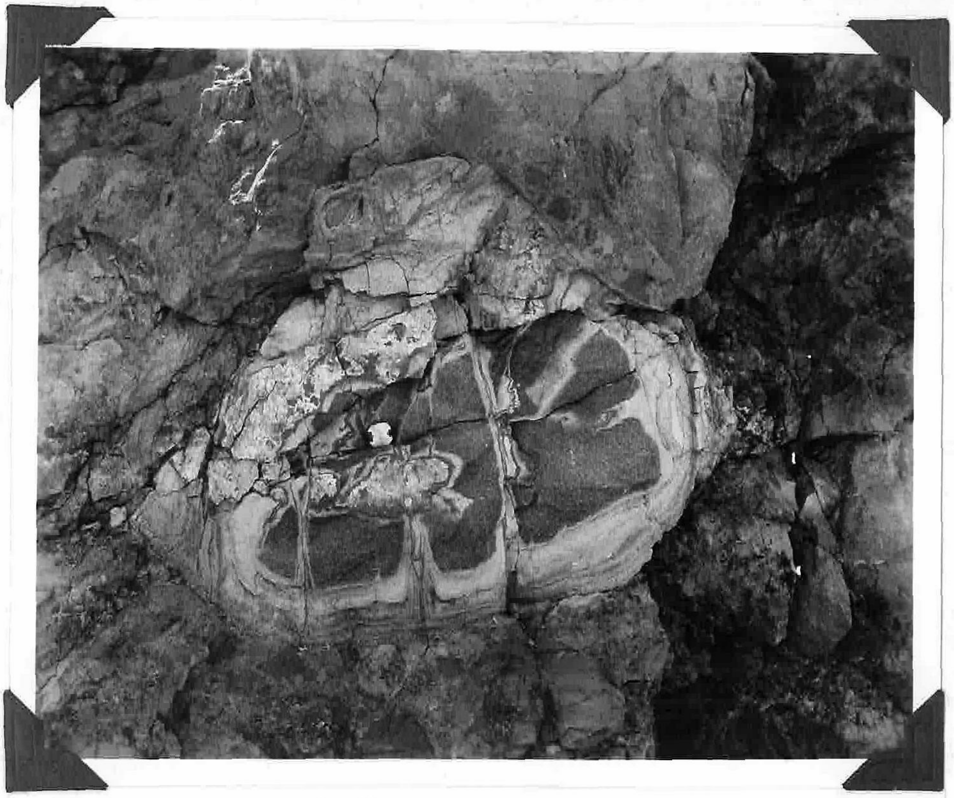

Fig. 12

BOULDER OF GLASSY LATITE IN SPILLWAY BRECCIA

At intersection of Arizona spillway road with main highway, looking south. Boulder is somewhat rounded. (N. P. S. No. 1014).

of the order of 1 mm., but does not show such a distinctive bedding or cleavage. The fragments in the grit, however, are visible megascopically and consist mainly of feldspar and Latite Flow-Breccia.

In thin section the sandstone variety shows fragments which are quite even granular, and angular to sub-angular. The bedding is accentuated by the alignment of elongate minerals, as biotite. The fragments are mainly of single crystals, plagioclase being dominant. The dark minerals are largely altered to chlorite, magnetite, and hematite, although a few crystals of biotite and hornblende still remain as such. Much of the groundmass of this rock consists of volcanic glass, probably derived from the Latite Flow-Breccia. The grit resembles the sandstone quite closely in thin section, except for the coarser grain size. The grains include crystals of plagioclase, biotite, magnetite, and hornblende; and rock fragments of Latite Flow-Breccia, Quartz-Monzonite, and Dam Breccia.

The deposition of the Spillway Breccia took place between eruptions of the Black Canyon lavas at a very rapid rate, since the fragments are so large and angular, and so poorly sorted. The lenses of sandstone and grit represent quieter conditions of sedimentation, but they are quite small in extent. The material travelled only short distances, as most of the fragments represent rocks which occur nearby. The Arizona spillway locality, (Fig. 6, p. 21), is a basin into which the breccia was almost literally dumped.

Since the formation is so variable, no purely petrographic designation would be applicable to the whole unit. Because of its major occurrence at the Arizona spillway, Ransome (3), p. 27, has named this formation the Spillway Breccia; this name will be retained.

Augite Latite

The Augite Latite is greenish grey to reddish grey in color, and is usually fine grained and compact. Generally white plagioclase and green pyroxene phenocrysts are visible.

Under the microscope, in thin section, the rock is very porphyritic in texture, with large phenocrysts present in a fine grained groundmass. The primary constituents of the phenocrysts are plagioclase, augite, and magnetite.

The plagioclase is euhedral to subhedral, and andesine of composition An_{47}. In a few instances orthoclase is intergrown with the andesine in the phenocrysts, but not with the same optical orientation. These phenocrysts are altered to calcite, at times almost completely.

The augite occurs as smaller crystals than the plagioclase, but is likewise euhedral to subhedral. It is colorless in thin section. Most of the augite is altered to a green fibrous uralite aggregate, plus calcite and iron oxides. The augite crystals are usually completely replaced, or not at all. This would indicate that the alteration was locally intense, though not affecting the entire rock. Most of the magnetite is euhedral, in isometric forms, and is probably primary; some of it, however, is a replacement of the augite.

The groundmass of the Augite Latite is hyalopilitic, consisting of feldspar laths in a glassy, partly devitrified, matrix. The feldspar has an index below or near balsam, and is probably orthoclase; the glass itself also has an index below balsam. Hematite and magnetite are present in the groundmass.

Mineralogically this formation is a latite, since both feldspars occur, plagioclase, (plus some orthoclase), in the phenocrysts, and orthoclase in the groundmass. The primary mafic mineral, however, is not the biotite or hornblende usual to a latite, but the more sub-silicic augite. This augite is visible megascopically in practically all occurrences of the formation;

generally, however, it is replaced by the green uralite. Inasmuch as the Biotite Latite formation has been given a purely petrographic designation, and since the formation under consideration could not very satisfactorily be given a geographical designation, it has been named the Augite Latite.

Ransome (3), p. 32, has named this formation the "Basic Latite", but qualifies this designation as follows: "... the adjective basic would not be applied ..... were it not desirable to distinguish it from the Biotite Latite ...". The adjective basic would connote a chemical composition rather high in lime and magnesia, and low in alkalies. This is, however, not the case, as shown by a partial chemical analysis of a specimen from the formation, taken just northwest of the dam, quoted from Ransome (3), p. 31. These data are compared with those of Daly (12), pp. 21-26, for average compositions of trachyte, sub-alkaline trachyte, latite, and andesite.

	Augite Latite	Average Trachyte	Average Sub-alkaline Trachyte	Average Latite	Average Andesite
SiO_2	59.13%	60.68%	63.91%	57.65%	59.59%
MgO	2.25	1.12	1.14	3.22	2.75
CaO	3.55	3.09	2.81	5.74	5.80
Na_2O	2.90	4.43	3.08	3.59	3.58
K_2O	6.02	5.74	5.80	4.39	2.04
Σ alkalies	8.92	10.17	8.88	7.98	5.62

Comparisons between the Augite Latite and average latite show that the former is actually lower in lime and magnesia, and higher in total alkalies, than the latter. Hence it could hardly be a basic latite. The Augite Latite closely resembles average sub-alkaline trachyte in composition, especially in the alkalies; it is also close to average latite. The rock is a latite, however, rather than a trachyte, since abundant andesine occurs as phenocrysts.

Sugarloaf Tuff

The Sugarloaf Tuff is a thin and localized deposit of tuff, occurring chiefly at Sugarloaf Hill. It is light yellow on fresh fracture, and greyish yellow when weathered. Most of the exposed portion of this rock is quite crumbly, and extremely difficult to sample. The fragments are of medium grain and uniform in size, consisting dominantly of glassy plagioclase, with lesser amounts of biotite. The groundmass is fine grained and shows very fine bedding, suggesting that the tuff may have been reworked by water to some degree.

The dominant feature of the Sugarloaf Tuff in thin section is the occurrence of large, euhedral to subhedral, crystals of plagioclase in a fine grained hypocrystalline groundmass. Their composition is andesine, An_{44}. Some of these plagioclase crystals show minor clastic effects, such as granulation and bending. Other phenoclasts include biotite, brown hornblende, and magnetite; many of these mafic crystals have been replaced by iron oxides. In addition to the phenoclasts, many glassy fragments of generally latitic character, showing various degrees of reaction with the groundmass, are present.

The groundmass is pink to light brown in color, and is a partly devitrified glass. Its index is well below balsam, and it is probably latitic. The groundmass is well bedded on a fine scale, and many of the bedding lines bend around the phenoclasts.

Stratigraphically, this formation underlies the Biotite Latite, and petrographically it is quite similar to it. The tuff probably represents minor explosions, immediately preceding the extrusion of the Biotite Latite lavas. It is of pyroclastic origin, but water may have played some part in the sedimentation process.

According to the classification of Wentworth and Williams (13) this formation is a crystal tuff, since practically all of the fragments are crystals. The formation has been given the geographical name of Sugarloaf Tuff, however, because of its major occurrence there.

Biotite Latite

The Biotite Latite is an easily recognized formation, its outstanding characteristic being its pink to pinkish grey color. Many flakes of biotite are seen on the fresh fracture of this rock; in places, white to glassy plagioclase phenocrysts are also visible. Much of the rock shows flow structure in hand specimen, this being especially true at the Bootleg Canyon locality. The groundmass is fine grained and compact. A notable feature of this rock is the amount of secondary quartz present; it occurs as amygdule fillings of the vesicular varieties, and as vein fillings. In certain localities, the silica is cryptocrystalline, as onyx, agate, etc. The normal facies of the Biotite Latite is locally highly altered, intensifying the red color of the formation. (Chapter IV - gypsum and silica minerals).

The basal flow of the Biotite Latite often grades into a black, perlitic variety, which owes its origin to rapid cooling of the lava. This facies is obsidian-like, showing at times perlitic texture, and is quite brittle. Many large white phenocrysts of plagioclase, and black flakes of biotite, occur. This facies weathers to a yellow or white crumbly mass when exposed.

In thin section, the normal facies is a porphyritic rock, with large euhedral phenocrysts in a hypohyaline groundmass. Most of the phenocrysts are of plagioclase, andesine of composition An_{45}, and are highly zoned. Biotite is next in abundance; most of it is brown, but an occasional green flake appears. The biotite of the Bootleg Canyon locality is more reddish than that of Black Canyon. Next in order of abundance are brown to green hornblende, and orthoclase. Only one quartz phenocryst was observed; this euhedral crystal was embayed by the groundmass, producing a reaction rim. Many apatite grains are included by the biotite and the plagioclase.

The groundmass is hypohyaline, and slightly devitrified. Its index of refraction is below balsam, pointing to a latitic composition for it. A few laths of orthoclase occur in the groundmass, which is brown in color; abundant magnetite occurs. The groundmass of the Bootleg Canyon rock is almost crystalline, due to the presence of considerable calcite, of secondary occurrence, in the thin section. This alteration, more abundant at the Bootleg Canyon locality than at the Black Canyon, has also attacked the phenocrysts to some extent.

The rock is traversed by many quartz veinlets. The quartz is very coarse grained, and clear, except for the inclusions of the latite. Spherulitic aggregates of chalcedony occur in the quartz, from the Black Canyon rock. Most of the fibres are length-fast, but a few are length-slow. A concentric structure is combined with the radial. The calcite is later than the quartz, since veinlets of it cut those of the quartz.

The glassy facies of the Biotite Latite is a typical perlite in thin section. The perlitic texture, consisting of a spherical to rounded arrangement of cooling cracks in a hypohyaline groundmass, is pre-eminent. The phenocrysts, which comprise 10 to 15% of the slide, are markedly euhedral. The dominant mineral is plagioclase, andesine in composition. Other minerals are brown biotite, brown hornblende, magnetite, and traces of orthoclase. The feldspar is highly zoned, and contains numerous inclusions, as does the biotite.

The groundmass is partly devitrified along the perlitic cracks; orthoclase is the principal mineral so formed. The main portion of the groundmass is white, and has an index of refraction below balsam, being latitic in composition. Many minute crystallites, probably of feldspar, occur; the usual forms are trichites and belonites.

One reason for the fresh appearance of this perlite in thin section is the almost complete lack of alteration. It differs from the usual variety in being somewhat more basic in composition; the usual variety is a rhyolite perlite.

This formation has been named the Biotite Latite by Ransome (3), p. 33, because of the abundant glittering flakes of biotite characteristic of it. Although the chemical composition given for this rock (3), p. 33, is higher in silica than the average latite, and near to quartz-latite, Ransome's designation will be retained. The following is a comparison between the partial chemical analysis of the Biotite Latite, sample taken from north-northwest of the dam, and Daly's (12), pp. 25 and 23, average values for dacite (quartz-latite) and latite:

	Biotite Latite	Average Dacite	Average Latite
SiO_2	66.58%	66.91%	57.65%
MgO	1.38	1.22	3.22
CaO	4.37	3.27	5.74
Na_2O	3.79	4.13	3.59
K_2O	4.58	2.50	4.39
Total alkalies	8.37	6.63	7.98

The Biotite Latite, although nearer to dacite in magnesia and lime, and also in silica, is closer to latite in soda, potassa, and total alkalies. Since the high proportion of alkalies is a dominant feature for the Black Canyon lavas, the designation of latite for this formation seems applicable.

Chlorophaeite Tuff

Compared to the Sugarloaf Tuff, the Chlorophaeite Tuff is quite different, both texturally and mineralogically. It is green on fresh fracture, has a clastic texture, and is very fine grained. Upon exposure, this tuff turns brown, and weathers spheroidally.

In thin section, the rock appears clastic and tuffaceous in texture. Sub-angular fragments of trachydolerite, resembling the rock of that formation, and of various primary minerals, including augite, labradorite feldspar, magnetite, hornblende, and biotite are present.

Of especial interest is the occurrence of a green secondary mineral, which is believed to be chlorophaeite. It occurs as pellets, and is a major constituent of the groundmass. It has an index near to balsam, and is amorphous. The deep yellow-green to blue-green color, however, gives the mineral an anomalous birefringence. Some of the aggregates are fibrous, and may be in part chlorite. Much orange-brown material is present in the groundmass; according to Fuller (14), who has studied this mineral in a southeastern Oregon occurrence, this is possibly an oxidation product of the chlorophaeite. Much of the orange-brown material, however, consists of secondary iron oxides. Chlorophaeite has the composition, $(Fe, Al)_2O_3 \cdot 2(Fe, Mg, Ca)O \cdot 4SiO_2 + 10\ H_2O$, and is formed deutericly by hydrothermal action on ferro-magnesian minerals, and on the basic constituents of the groundmass of basic rocks of volcanic origin. It is a complex gel mineral, and varies in composition over moderate ranges.

Peacock and Fuller (15), p. 364, have made chemical analyses of this mineral and of the dike in which it occurred at a Columbia Plateau locality, and have found that the rock most closely approached a trachydolerite in composition. It is thus very likely that the Chlorophaeite Tuff formation here represents volcanic explosions preceding the intrusion and extrusion of the Trachydolerite formation.

The remainder of the groundmass of the rock consists of primary plagioclase, and secondary chlorite and calcite, with hematite and magnetite. Moreover, many of the plagioclase phenoclasts are partially to completely replaced by calcite.

According to the classification of Wentworth and Williams (13), this formation would be a crystal-lithic tuff, since crystal fragments predominate over rock fragments. But because of the distinctive color of the formation, due to the presence of the chlorophaeite, it has been named the Chlorophaeite Tuff.

Trachydolerite

The typical appearance of the Trachydolerite in the field is a light grey rock, which is often quite crumbly on the surface. On fresh exposure, the rock is dark grey in color, and varies from compact to vesicular in texture. The amygdules are generally filled with calcite, which also occurs as tiny veinlets, and disseminated throughout the mass; it varies from coarsely crystalline to fine grained in texture. The only phenocrysts visible are small light green crystals of pyroxene. Many rusty specks occur over the surface of the rock; these are possibly pseudomorphs after olivine.

In thin section, the texture of the rock is dominantly hyalopilitic. Many plagioclase phenocrysts have a felted arrangement in a hypohyaline groundmass, consisting dominantly of a dark glass. No flow structure orientation exists with regard to the phenocrysts as a whole, but small groups of laths show tendencies towards alignment.

The plagioclase is dominantly lath-shaped, but a few crystals are more or less equant. Their length ranges from 2 mm. down to the groundmass size. None of them have conspicuous albite twinning, and the determination of the composition was not simple. From the maximum angle found, the composition seems to be calcic andesine. A few of the smaller grains have an index of refraction below balsam, and are probably orthoclase.

Many phenocrysts of pale green augite are also present. It is euhedral, and is earlier than the plagioclase in crystallization. Much magnetite is present, both in the groundmass and in the phenocrysts. Part of the latter is primary, the remainder being secondary, probably after olivine.

The groundmass consists mainly of a dark brown glass, which is only slightly devitrified. This glass shows noteworthy colloform banding, which is to some extent controlled by the phenocrysts. Its index of refraction is very near to balsam, suggesting the presence of potassa or soda. The other primary constituents of the groundmass are plagioclase, augite, magnetite, and probably orthoclase.

The chief secondary mineral in the rock, as evidenced also by the hand specimen, is calcite. It is a vesicle filling, where it shows a radial orientation, and is a replacement mineral of the phenocrysts, both plagioclase and augite, and of the groundmass. In the vesicles, especially, it is rather coarsely crystalline. The other secondary minerals include hematite, magnetite, and serpentine.

On the basis of mineralogy, the rock lies between a latite and a basalt (or andesite), having the groundmass of the former, but the phenocrysts of the latter. Ransome (3), p. 38, quotes a partial chemical analysis of this rock, sample taken from north-northwest of the dam, which is compared below with the data of Daly (12), pp. 23-30, for average latite, andesite, basalt, and trachydolerite. The analysis of the Augite Latite, given on p. 48, is repeated here.

	Trachydolerite of Black Canyon	Average Latite	Average Andesite	Average Basalt	Average Trachydolerite	Augite Latite of Black Canyon
SiO_2	52.15%	57.65%	59.59%	49.06%	49.20%	59.13%
MgO	5.14	3.22	2.75	6.17	4.43	2.25
CaO	6.45	5.74	5.80	8.95	7.74	3.55
Na_2O	3.20	3.59	3.58	3.11	4.54	2.90
K_2O	4.38	4.39	2.04	1.52	3.19	6.02
Σ alkalies	7.58	7.98	5.62	4.63	7.73	8.92

According to these analyses, the rock is nearest to average latite and trachydolerite. Of the two, on the basis of total alkalies, silica, and magnesia, it lies closer to trachydolerite; on the basis of lime, soda, and potassa, it is nearer to latite. Ransome (3), p. 40, has named this rock Trachydolerite rather than latite, because of the presence of pseudomorphs after olivine. The above analyses show that the rock is lower in alkalies and silica, and higher in basic oxides than the Augite Latite; hence the name Trachydolerite will be retained.

Dry Camp Breccia

In contrast to the Dam Breccia and the Spillway Breccia, the Dry Camp Breccia is very well stratified and sorted. (Fig. 10, p. 27). Many rounded cavities have been weathered out along stratification planes, accentuating the bedding. The hand specimen of this formation shows a very compact sedimentary breccia, consisting of angular fragments of monzonitic and granitic rocks, plus a smaller proportion of volcanic rocks, of angular shape and up to 1 inch in size, embedded in a fine grained reddish matrix. This rock is, in fact, so well indurated that it fractures through the fragments almost as easily as around them.

In thin section, the rock consists of sub-angular to angular fragments of various rock types in a reddish fine-grained matrix. The dominant rock constituting the fragments is a granitic rock, consisting mainly of quartz, oligoclase, and orthoclase, with a marked development of sub-myrmekitic texture. This rock type has not been met among the rocks of the area which have been studied petrographically, and probably is derived from the granitic rocks of the Black Mountain Range, to the east. Other rock types identifiable among the fragments include Quartz-Monzonite, Altered Monzonite Porphyry (?), and Biotite Latite. Most of the mafic minerals in the fragments have been replaced by iron oxides, rendering specific identification of these fragments difficult.

The red matrix is fine grained, and consists of hematite, magnetite, quartz, and feldspar. Much secondary calcite, sericite, and kaolinite are present in the matrix, and also in the fragments. One small quartz veinlet traverses the slide; this possibly is of the same general period of mineralization as the quartz so characteristic in the Biotite Latite. This mineralization in the breccia may be the source for some of the quartz present in the section as individual grains; the quartz in the granitic fragments, however, is definitely primary with respect to those fragments.

This rock has been named the Dry Camp Breccia by Ransome (3), p. 14, because of its occurrence at Dry Camp Wash, which drains into the Colorado River, north of the dam. Inasmuch as geographical, rather than petrographic, names have been applied to the other sedimentary breccia formations, the name given to this formation will be retained.

Petrogenesis of the Younger Volcanic Series

The discussion of the petrogenesis of the Younger Volcanic Series will here be limited to those rocks of volcanic origin, the remaining members being sedimentary breccias, inter-volcanic in time of deposition. These volcanic rocks, in chronological order, are Latite Flow-Breccia, Augite Latite, Biotite Latite, and Trachydolerite. Associated with the latter two formations are the Sugarloaf Tuff and Chlorophaeite Tuff, respectively, which probably represent minor explosions just previous to the main periods of eruption.

Mineralogically, these rocks are similar in that they contain both feldspars, plagioclase of composition andesine or labradorite, mainly as phenocrysts, and orthoclase, chiefly in the groundmass. There is a relatively greater variation among these rocks in the nature of the mafic minerals. Biotite is the principal dark mineral in the Latite Flow-Breccia and in the Biotite Latite; augite is dominant in the Augite Latite and in the Trachydolerite. Pyroxenes may have been present also in the other two rocks, but, if so, they have been completely altered to iron oxides. Free quartz is absent or negligible in all of these rocks; the only formation which possibly contains olivine is the Trachydolerite.

Further indication of the similarity between these rocks is furnished by the data from the chemical analyses. No representative analysis is quoted by Ransome for the Latite Flow-Breccia, but a partial analysis of a specimen from this formation, which differs from the usual type in that the flow-breccia fragments are absent, is given (3), p. 25. This analysis will be used as possibly suggestive of the general chemical nature of that formation. The following are the analyses of the volcanic rocks of this series:

	Latite Flow-Breccia	Augite Latite	Biotite Latite	Trachydolerite
SiO_2	65.65%	59.13%	66.58%	52.15%
MgO	0.68	2.25	1.38	5.14
CaO	1.10	3.55	4.37	6.45
Na_2O	1.96	2.90	3.79	3.20
K_2O	8.85	6.02	4.58	4.38
Σ alkalies	10.81	8.92	8.37	7.58

CHEMICAL COMPOSITION OF ROCKS OF YOUNGER VOLCANIC SERIES

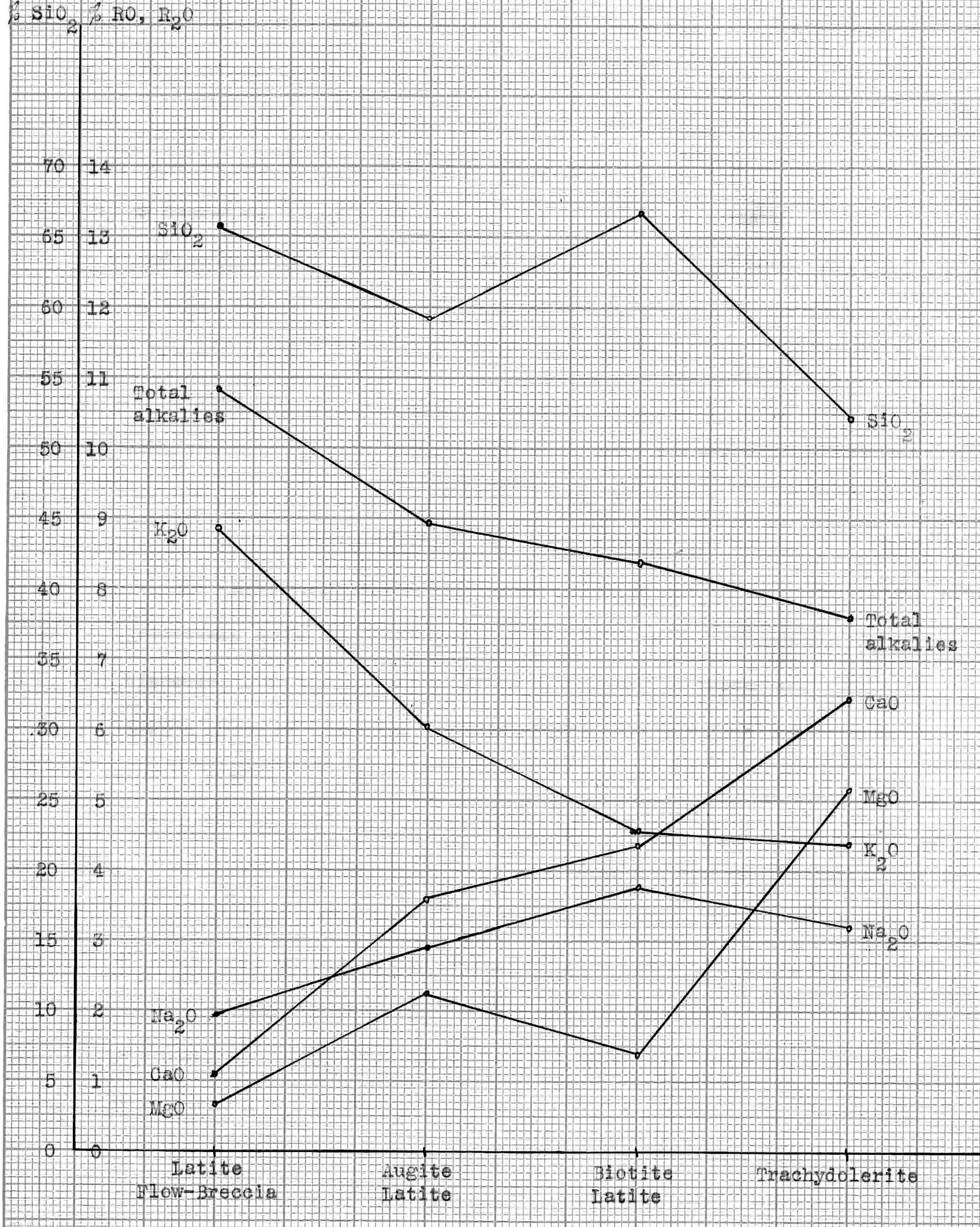

Fig. 13

These partial analyses are plotted on Fig. 13 for the various rocks, in chronological order. This type of diagram, rather than a silica variation diagram, has been used, because it more clearly shows the trends of composition variation during the eruption cycle. A silica variation diagram could have been used, were it not for the fact that the percentage of silica does not increase, or decrease, consistently in the chronological succession.

The most outstanding chemical feature of these rocks, as seen from the analyses, is their high percentage of total alkalies, especially potassa. These rocks are all latitic in generally petrological character, their alkali content being higher than for andesite or basalt.

It seems quite certain that these volcanic rocks are all differentiation products from one primary magma, of generally latitic character, and rather high in potassa and in total alkalies. Fig. 13 shows the general trend of the proportion of the various oxides as the differentiation proceeded. The lavas become progressively lower in total alkalies and in potassa; higher in the basic constituents, lime and magnesia; slightly higher in soda; and slightly lower in silica. Thus the general trend is from a more alkaline and silicic rock to one more basic.

The volcanic rocks of the Older Volcanic Series, and the Fortification Hill Basalt, which are older and younger, respectively, than the Younger Volcanic Series, give no indication, in hand specimen or in thin section, of such a high proportion of potassa and total alkalies, which is characteristic of the latter. Although it is possible that chemical analyses, made in the future, from samples of these two formations may show that these rocks are as high in potassa and total alkalies, this is considered as unlikely. Hence the character of the magma giving ride to the rocks of the Younger Volcanic Series is quite distinct from that of the magmas of the Older Volcanic Series and of the Fortification Hill Basalt.

FORTIFICATION HILL BASALT

The Fortification Hill Basalt formation consists of superposed lava flows, with interbedded slaggy material. The flows are generally vesicular, some being more so than others; many of the vesicles are filled with calcite, which material is abundant on the top surface of Fortification Hill as a travertine material. (Chapter IV - calcium carbonate).

The basalt is dark grey and amygdaloidal when fresh; it turns yellow to brown upon exposure. Many of the vesicles, as seen from the calcite filling, are stretched in a common direction, indicative of the flow structure. Many small rusty specks are present; they are doubtless pseudomorphs after olivine. A few small phenocrysts of light green augite and white feldspar are detectable.

In thin section the rock is holocrystalline and intersertal in texture. The essential minerals are plagioclase and augite. The plagioclase is mainly lath shaped, whether occurring as phenocrysts, or in the groundmass. The laths are subhedral to euhedral, often many millimeters in length, but show no obvious orientation in the section. Their composition, as calculated from the twinning angles of the very prominent albite twinning lamellae, is sodic bytownite of composition An_{71}. Very little of the plagioclase shows any zoning.

The augite is colorless to pale green, subhedral, and usually equant in shape. Very few phenocrysts of augite occur, most of it occurring in intersertal relationship to the plagioclase.

Other minerals present as phenocrysts include magnetite and pseudomorphs of red iddingsite after olivine. The latter replacement is complete, and the crystals are often as large as 2 mm. in size. Part of the iddingsite has been converted to iron oxides.

Many vesicles are filled with coarsely crystallized calcite; the repladement of primary minerals by calcite, however, is not very extensive.

On the basis of mineral composition, this rock is a true basalt. It does not seem to be at all related to the older latitic lavas of the Younger Volcanic Series. Because of its occurrence as a capping of that prominent landmark to the northeast of Boulder Dam, this formation has been named the Fortification Hill Basalt.

Chapter IV

MINERALOGY AND ECONOMIC GEOLOGY

Many minerals occur within the region around Boulder Dam, but rarely in sufficient concentrations to make their extraction profitable. Almost all mining in the area is confined to prospecting by individuals; only in a very few instances have deposits been staked out and the claims registered. Of the various minerals in the area, oxides of manganese, turquoise, and alum have at times been considered as possibly of economic value.

MANGANESE OXIDES

As is common in arid regions, manganese oxides are associated with the rocks here. Coatings of the oxides are notably present in shear zones; the presence of this black coating has proved an excellent criterion for determining faults or joints. The oxides often occur as dendrites in the joints of the rocks of the Older Volcanic Series.

The only locality where manganese mining is at all active is the mine known as the Red Devil Claim No. 1, located in the hills west of Hemenway Wash, and 1/4 mile west of the most southerly of the two prominent U-bends in the railroad. The oxides are here associated with barite, and are probably later in age. Many prospect holes for manganese were found, but no active mining was observed.

TURQUOISE

Also associated with the barite are the deposits of turquoise. In general the ore is too lean, and the mineral in too small aggregates for profitable extraction. At one locality situated at the base of the hills west of Hemenway Wash, 1 mile from the main highway, and 0.6 mile from the beach road, is the Apache Claim No. 4. In addition to the turquoise, primary chalcopyrite and bornite occur here, possibly the source of the copper for the secondary turquoise.

ALUM

Alum is present in two localities in the area: one, 1 mile west, and the other, 3 miles east of Boulder City. It occurs in the Altered Monzonite Porphyry (?), and has accompanied the further alteration of that rock. This second stage of alteration has changed the red color of the altered rock to yellow. The source of sulfuric acid for this hydrothermal alteration was the pyrite, previously disseminated in the rock. The alum has subsequently been concentrated in small pockets. Although these deposits have been described (6), p. 147, as being of potash-iron alum, chemical tests have shown it to be the potash-aluminum variety. The quantity of alum represented by these two deposits is not of economic importance.

ALUNITE

Alunite has been formed by much the same processes by which the alum has been produced. The deposits of alunite within the area are very few, and their extraction has not been attempted.

BARITE

Perhaps the most notable mineralization within the area is that of barite. The area of greatest abundance of this mineral is in the Older Volcanic Series of the hills west of Hemenway Wash, and in the section of these hills situated 1/3 of the distance from "Fault" Canyon to Lake Mead. The mineralization extends over a zone about 1/2 mile long, and more than half way to the crest of the hills. So intensely has this section been mineralized with barite, that this mineralized zone appears light brown in color, when viewed from the highway, while the unmineralized portions of the hills appear dark brown.

Fig. 14

BARITE MINERALIZATION IN OLDER VOLCANIC SERIES

Apache Claim No. 4, west of Hemenway Wash. Veinlets form intricate stockwork. Turquòise is associated mineral. (N. P. S. No. 1028).

The pattern of the barite is an intricate stockwork of intersecting veinlets. The veinlets range in thickness from 1 mm. or less to 3-4 inches, while individual crystals up to 1 inch in size have been found. (Fig. 14). In the barite, and apparently later in age, are oxides of manganese and copper minerals, as mentioned above.

All mining carried on in the barite is for the associated manganese oxides and copper minerals.

GYPSUM

Gypsum is very abundant in the area, and is most extensive in the regions of greatest rock alteration. A massive variety, which is in cases the pinkish tinted variety, alabaster, is associated with the areas of hydrothermal alteration of the Altered Monzonite Porphyry (?), and accompanies the alum, produced by the alteration.

At one locality, situated just south of the Lower Portal road, and 1/3 way down from the upper terminus, the Biotite Latite has locally undergone intense alteration, accompanied by the formation of much gypsum. The mineral is fibrous, and is the variety satin spar. These masses are generally 1/2 to 1 inch in thickness, and occur as veins in the altered rock. An interesting rock formation observed here is a pillar of this altered rock, which has a bright red capping. This pillar, 15 feet high and 3 feet in diameter, resembles an ice cream cone from a distance. (Fig. 15).

SILICA MINERALS

Silica mineralization is locally abundant, and especially so on the Arizona side of Black Canyon, between the main highway and Sugarloaf Hill. It occurs almost entirely in the Biotite Latite. As explained in the chapter on areal geology, the fact that similar silica mineralization occurs in Bootleg

Fig. 15

PILLAR OF ALTERED BIOTITE LATITE

South of Lower Portal road. Pillar traversed by many veins of gypsum, variety satin spar. (N. P. S. No. 1015).

Canyon, in the hills west of Hemenway Wash, led in part to the correlation of this rock unit with the Black Canyon Biotite Latite.

The type of mineralization varies from quartz crystals in the amygdules of the Biotite Latite, to veins and replacements of opal and chalcedony, and such cryptocrystalline varieties as jasper, onyx, and agate. Some of the coloring is very beautiful, being of shades of blue, orange, pink, and white. When polished, this material makes very attractive specimens.

CALCIUM CARBONATE

Calcium carbonate is not found as crystallized calcite, except in the amygdules of the Trachydolerite and the Fortification Hill Basalt. But associated with the basalt is a variety of the carbonate which is travertine-like in appearance. This material is not entirely calcareous, and may be in part siliceous.

Chapter V

STRUCTURE

Much of the structure of the area has already been indicated in the chapter on areal geology, in connection with the establishment of the age relationships of the various formations. There are, however, certain features relating to the internal structure of the various formations, relations between different formations, and the relation of the Boulder Dam area to the regional structure, which should be considered here.

The pre-Cambrian rocks have two occurrences in the area. The first is at Saddle Ridge. This small island is a remnant of a once much more extensive mass. Part of its present low lying position, however, may be due to downfaulting relative to the higher rocks to the south and east.

The other pre-Cambrian occurrence, the Black Mountain Range, undoubtedly owes much of its height to faulting, probably related to the general period of Basin and Range faulting. The gravels of the Muddy Creek Formation, and other sedimentary formations further south, which slope away from the mountain front, clearly indicate such faulting. However, most of the relief of the range in this area is due to the removal of soft sediments to the west by the Colorado River drainage. The faulting is dated by Longwell (4), p, 1467, as Pliocene (?); this accords with observable relationships.

Because of the highly altered condition of the Altered Monzonite Porphyry (?), very little has been determined concerning the internal structure of this unit. This formation occupies a thin belt striking east-northeast - west-southwest, and lying north of Black Canyon. The central portion of this belt has been removed by erosion, or is now covered by Lake Mead. At its contact with the Black Mountain granitic rocks, it appears to abut into the latter.

This is doubtless due to the upfaulting of the Black Mountain mass. Moreover, the occurrence of the Altered Monzonite Porphyry (?) in the Bootleg Canyon area is due to the upfaulting of it against the Older Volcanic Series.

The Quartz-Monzonite is believed to be intrusive into the Altered Monzonite Porphyry (?) and any pre-Tertiary rocks present at the time of intrusion. The possibility exists, however, that this formation grades into the Altered Monzonite Porphyry (?), differing from it only in intensity of alteration. The chief evidence for considering them as two formations is the sharp, straight contact which often separates them, as, for example, in the hills southeast of Hemenway Wash.

The structural history of the Older Volcanic Series has been predominantly one of faulting. The internal structure of this series, as seen within the area, is rather simple. It consists of a thick series of apparently conformable andesite flows and interbedded sedimentary breccias, with dips ranging from approximately 60° in the hills west of Hemenway Wash, to somewhat less where the formation emerges from under the Younger Volcanic Series and Dam Breccia, in Black Canyon, south of the dam. Other parts of this formation are nearly horizontal, as in the hills southeast of Hemenway Wash.

The main mass of the Older Volcanic Series in the area is in the hills west of Hemenway Wash. The northeast face of this block, including far more than the area represented on the geologic map, appears quite straight when viewed from a distance; this may possibly be a fault or fault-line scarp. The side of the block facing Hemenway Wash, however, owes most of its relief to erosion.

The contact between the Older Volcanic Series and the Altered Monzonite Porphyry (?) in these hills is the prominent fault, whose topographic expression is the deep canyon, here designated as "Fault" Canyon. This fault trends northwest-southeast and is quite steep. In this fault block of Altered Monzonite Porphyry (?), one small block of the Older Volcanic Series occurs in contact with the Altered Monzonite Porphyry (?), against a steep fault. From the geological evidence, it seems possible that this fault is a continuation of the main fault described above, but displaced from it laterally, probably by a cross-fault.

To the northeast of this block of the Older Volcanic Series is the anomalous block of Biotite Latite (of the Younger Volcanic Series), described in the chapter on areal geology, p. 23. The formations are in contact on a fault striking northwest-southeast, and dipping steeply to the northeast.

Fig. 16 is a diagramatic representation of the above structural relations in Bootleg Canyon.

In Bootleg Canyon, and across from the localites above described, is a flat lying plate of Altered Monzonite Porphyry (?) upon what appears to be a mass of Older Volcanic Series. Although overthrusting has not been found to be an important structural feature in the area, it is possible that this represents an overthrust, with the direction of thrusting from south to north. (Fig. 17).

The Dam Breccia is localized in occurrence to the lower walls of Black Canyon, where it underlies the Younger Volcanic Series and overlies the Older Volcanic Series. The dips in the Dam Breccia are often as steep as 60°. There is a definite unconformity between this formation and the overlying Latite Flow-Breccia of the Younger Volcanic Series, and a probable unconformity between it and the underlying Older Volcanic Series.

The Younger Volcanic Series is essentially a block tilted to the northeast and bounded by faults on two of its sides. This tilting and faulting was to some extent contemporaneous with the deposition of the series, since the dips

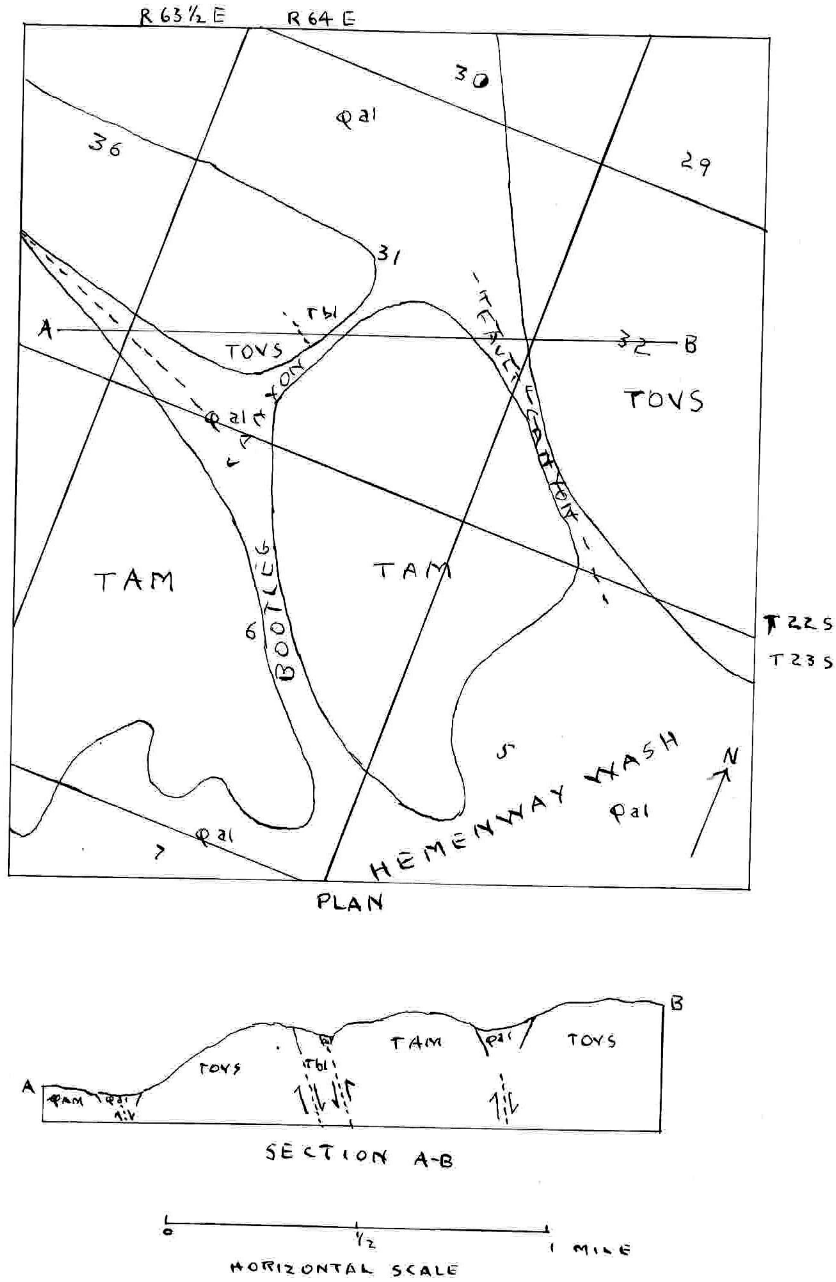

Fig. 16

DIAGRAM OF STRUCTURAL RELATIONS IN BOOTLEG CANYON

Vertical scale generalized and exaggerated. Qal - alluvium. Tbl - Biotite Latite. TOVS - Older Volcanic Series. TAM - Altered Monzonite Porphyry (?).

——— Contact with alluvium. - - - - - - Fault.

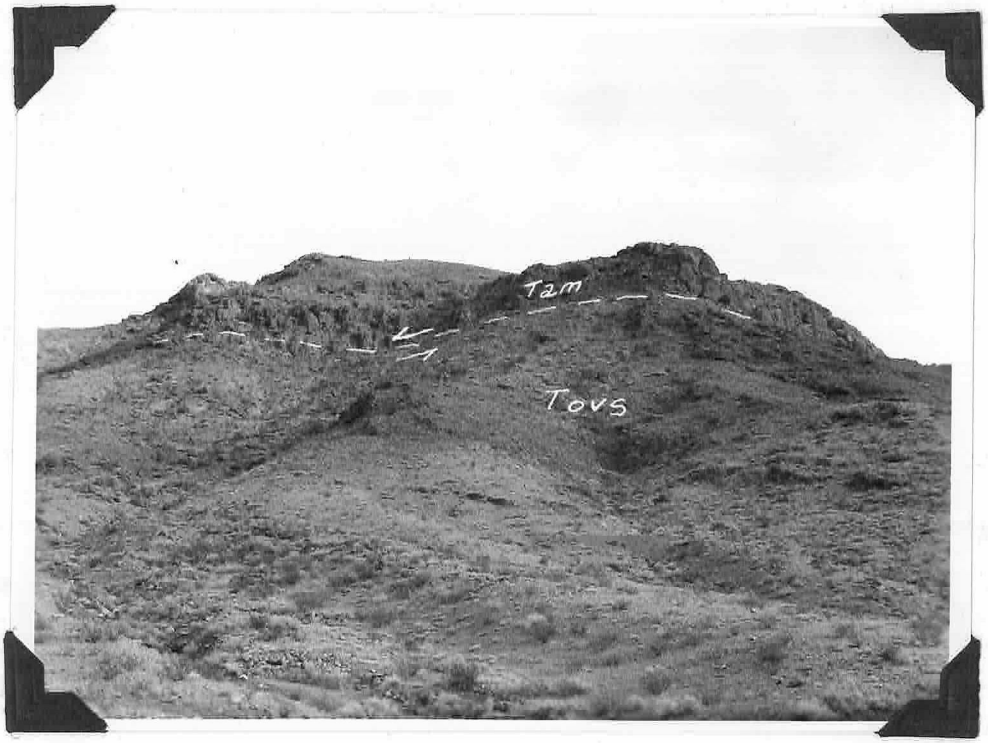

Fig. 17

OVERTHRUST OF ALTERED MONZONITE PORPHYRY (?) OVER OLDER VOLCANIC SERIES

East of Bootleg Canyon, south of summit. Contact dips slightly to south. (N. P. S. No. 1029).

are progressively lower in the younger formations. The dips are to the northeast and range from 60° in the lower members to 20° in the upper members. To the west the Younger Volcanic Series is in fault contact with the Older Volcanic Series. (Fig. 5, p. 20). To the north the lavas are abruptly terminated by Hemenway and Deadman Washes. It is possible that a fault of large displacement is buried under Lake Mead. In this case the lavas would have been uplifted to the north, and subsequently removed by erosion. This possibility is suggested by Ransome (3), p. 4.

To the east the lavas disappear under the various Pleistocene and Recent gravels. Southward the lavas continue beyond the area mapped. The Biotite Latite is known, according to Ransome (3), p. 14, for many miles south of Boulder Dam.

The internal structure of the Younger Volcanic Series is quite complicated. Reference is made to Ransome's report (3), pp. 42-53, for a more complete discussion of this feature. In general, the lavas are dislocated by a series of northwest-southeast striking faults with steep dips. The formations are generally downdropped to the northeast.

The Younger Volcanic Series is unconformable with the Older Volcanic Series and the Dam Breccia, where they occur in contact. Moreover, the Dry Camp Breccia, upper member of the Younger Volcanic Series, is separated by an unconformity from the underlying Biotite Latite. Fig. 18 shows the relationships of the lower members of the series, and Fig. 10, p. 27, shows the Dry Camp Breccia lying upon the Biotite Latite.

The remaining members of the Younger Volcanic Series consist of a series of conformable lava flows, tuff formations, and sedimentary breccias, deposited in basins within the lavas; and the Trachydolerite, which occurs as dikes, sills, and rarely as flows.

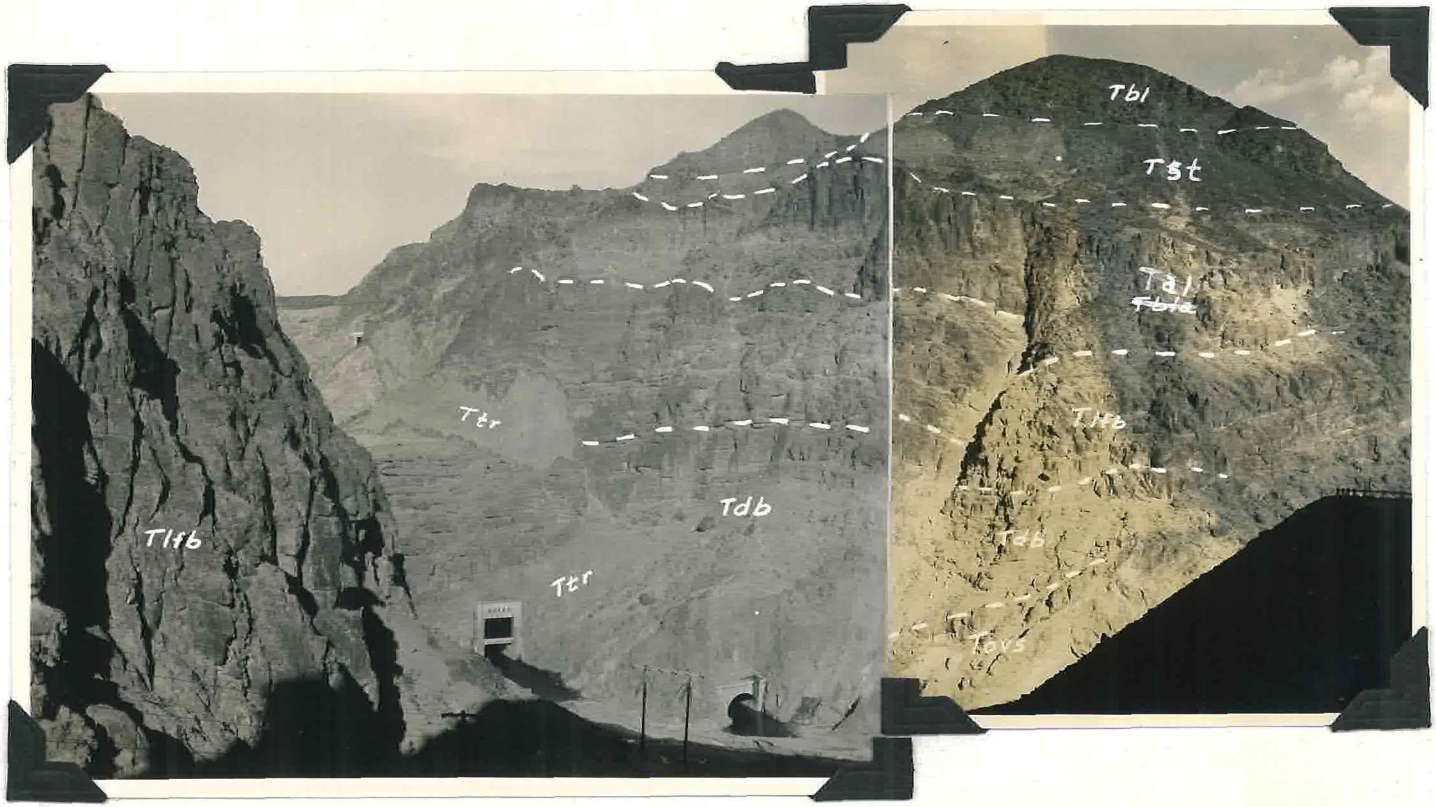

Fig. 18

ARIZONA WALL OF BLACK CANYON, SOUTH OF BOULDER DAM

Younger Volcanic Series unconformable upon Dam Breccia and Older Volcanic Series. Peak to right is Sugarloaf Hill. In center is sill of Trachydolerite, feeding a dike. (N. P. S. Nos. 1017 and 1023).

The Muddy Creek Formation, consisting of fanglomerate material, lies on a surface of Altered Monzonite Porphyry (?), produced by erosion. The Fortification Hill Basalt, consisting of 40 to 50 extensive lava flows, is conformable upon the Muddy Creek Formation. The relations between these two formations and the Younger Volcanic Series are not exposed, since the latter is cut off northward by Deadman Wash; it is quite likely, however, that there is a considerable time interval represented between the deposition of these two units.

APPENDIX

GEOLOGICAL COLUMN

	Symbol		Formation	Thickness
Quaternary	Qal		Alluvium	0-1000' (?)
		Uncon.		
Lower Pliocene (?)	Tb		Fortification Hill Basalt	400'
	Tmc		Muddy Creek Formation	500'
		Uncon.		
Middle or Lower Tertiary (?)	Tyvs		Younger Volcanic Series	1500-3000'
	Tdcb		Dry Camp Breccia	300-400'
		Uncon.		
	Ttr		Trachydolerite	0-50'
	Tct		Chlorophaeite Tuff	15'
	Tbl		Biotite Latite	200-400'
	Tst		Sugarloaf Tuff	75-200'
	Tal		Augite Latite	150-200'
	Tsb		Spillway Breccia	200-300'
	Tlfb		Latite Flow-Breccia	800-1000'
		Uncon.		
	Tdb		Dam Breccia	350'
		Uncon.		
Lower (?) Tertiary	Tovs		Older Volcanic Series	1500-2000'
		Uncon.		
	Tqm		Quartz-Monzonite	300-400'
		Intrusive		
	Tam		Altered Monzonite Porphyry (?)	400'
		Uncon.		
Pre-Cambrian	pЄgs		Pre-Cambrian Granitic Rocks	2000-3000'
			Pre-Cambrian Schist	200-300'

Fig. 19

GEOLOGIC MAP

INDEX TO LOCALITIES OF ROCK AND MINERAL SPECIMENS COLLECTED

ROCKS

Rock Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Biotite Latite	D-4-5-10-1	B.D.N.1●	Summit of Bootleg Canyon. (Corner to outcrop) -	31/6 T 22 S, T 23 S R 64 E; 550 Yards NORTH
Altered Monzonite Porphyry (?)	D-4-5-11-2	B.D.N.2°	1/4 mile W of Bootleg Canyon in continuation of "Fault" Canyon	31/6 T 22 S, T 23 S R 64 E; 640 Yards N 70° W
Hornblende Andesite (Older Volcanic Series)	D-4-5-12-3	B.D.N.3°°°	3/16 mile W of Bootleg Canyon in continuation of "Fault" Canyon	31/6 T 22 S, T 23 S R 64 E; 470 Yards N 70° W
Andesite (Older Volcanic Series)	D-4-5-12-4	B.D.N.4°	3/16 mile W of Bootleg Canyon in continuation of "Fault" Canyon	31/6 T 22 S, T 23 S R 64 E; 470 Yards N 70° W
Sedimentary Breccia (Older Volcanic Series)	D-4-5-13-5	B.D.N.5°	30' below top, 1/4 mile W of Bootleg Canyon, S of summit	31/6 T 22 S, T 23 S R 64 E; 550 Yards N 30° W
Quartz-Monzonite	D-4-5-14-6	B.D.N.6°	Top of Tank Hill, Boulder City	5|4 / 8|9 T 22 S, R 64 E; 480 Yards N 35° E
Andesite (Older Volcanic Series)	D-3-5-19-11	B.D.N.7●	Top of ridge, W of Hemenway [illegible] Wash; 1 1/4 miles W of highway	28|27 / 33|34 T 22 S, R 64 E; 440 Yards S 60° W
Latite Flow-Breccia	E-3-5-26-1	B.D.N.8●	Lower Portal road; 2/3 way down, at basalt dike	30|29 / 31|32 T 22 S, R 65 E; 550 Yards N 60° E

Rock Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Trachydolerite	E-3-5-26-2	B.D.N.9°	Lower Portal road; 2/3 way down. Dike	30|29 / 31|32 T 22 S R 65 E 550 Yards N 60° E
Sedimentary Breccia, Sandstone (Dam Breccia)	E-3-5-26-3	B.D.N.10°°	Bottom Lower Portal road., opposite lower Arizona portal, #4	30|29 T 22 S R 65 E 960 Yards S 70° E
Altered Monzonite Porphyry (?)	D-3-5-28-12	B.D.N.11•	1/4 mile E of beach cutoff, in canyon N of main highway	26|25 / 35|36 T 22 S R 64 E 390 Yards N 50° E
Sedimentary Breccia, Sandstone (Spillway Breccia)	E-3-5-29-4(a)	B.D.A.12(a)°°	Arizona spillway road, 30 yards west of main highway	3/10 T 30 N R 23 W 350 Yards N 30° E
Sedimentary Breccia, Grit (Spillway Breccia)	E-3-5-29-4(b)	B.D.A.12(b)°	Arizona spillway road, 30 yards west of main highway	3/10 T 30 N R 23 W 350 Yards N 30° E
Sedimentary Breccia (Dry Camp Breccia)	E-3-5-29-5	B.D.A.13°	Along main highway, in Arizona. S 70° W to Sugarloaf Hill. 1 mile to dam	3|2 / 10|11 T 30 N R 23 W 160 Yards S 60° W
Perlite (Biotite Latite)	E-3-5-30-6	B.D.A.14°	Along main highway, in Arizona. 1/2 mile to dam; WNW to dam.	3/10 T 30 N R 23 W 420 Yards N 55° E
Biotite Latite	E-3-5-30-7	B.D.A.15°	Along main highway, in Arizona. 1/2 mile to dam; WNW to dam.	3/10 T 30 N R 23 W 420 Yards N 55° E
Sugarloaf Tuff	E-4-5-31-1	B.D.A.16°	100' below summit of middle mesa, of three, about 1 mile S of dam; SW corner	15|14 T 30 N R 23 W 210 Yards N 45° W

Rock Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Chlorophaeite Tuff	E-4-5-31-2	B.D.A.17°	300 yards W of main highway, 1 1/2 miles to dam. Opposite Fortification Hill turnoff	11/14 T 30 N R 23 W 640 Yards S 10° W
Andesite (Older Volcanic Series)	E-3-5-32-8	B.D.N.18°	Bottom Lower Portal road; south end of catwalk	30|29 / 31|32 T 22 S R 65 E 950 Yards S 65° E
Augite Latite	E-3-5-32-9	B.D.A.19°	100' above summit of Arizona spillway road	3/10 T 30 N R 23 W 300 Yards N 3° E
Andesite (Older Volcanic Series)	D-3-5-32-13	B.D.N.20°	200 yards W, along main highway, from Observation Point turnoff	R 64 E 25|30 R 65 E T 22 S 575 Yards S 75° E
Basalt	E-3-5-48-10	B.D.A.21°	Middle of east rim of Fortification Hill	R 23 W T 31 N 24| / 25| (R 22 W) 1820 Yards S 70° E

Rock Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Hornblende Andesite (From dike)	E-4	B.D.A.53	In alluvium, exposed in roadcut, 9.0 miles E of dam along main highway	
Basalt	E-4	B.D.N.54(a)	11.0 miles from Boulder City in direction S 50° E, towards river, beyond gap in hills	
Scoria	E-4	B.D.N.54(b)	11.0 miles from Boulder City in direction S 50° E, towards river, beyond gap in hills	
Pumice	E-4	B.D.N.54(c)	11.0 miles from Boulder City in direction S 50° E, towards river, beyond gap in hills	

MINERALS

Mineral Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Wad	D-3	B.D.N.51(a)	Three Kids Mine - about 5 miles NW of Boulder City, and 16 miles SE of Las Vegas	
Gypsum (fibrous)	D-3	B.D.N.51(b)	Three Kids Mine - about 5 miles NW of Boulder City, and 16 miles SE of Las Vegas	
Barite	D-3 M-11	B.D.N.52(a)	Apache Claim No. 4, W of Hemenway Wash	28/27, 33/34; T 22 S, R 64 E; 480 Yards S 48° W
Turquoise (with barite)	D-3 M-12	B.D.N.52(b)	Apache Claim No. 4, W of Hemenway Wash	28/27, 33/34; T 22 S, R 64 E; 480 Yards S 48° W
Chalcopyrite (with barite)	D-3 M-13	B.D.N.52(c)	Apache Claim No. 4, W of Hemenway Wash	28/27, 33/34; T 22 S, R 64 E; 480 Yards S 48° W
Bornite (with barite)	D-3 M-14		Apache Claim No. 4, W of Hemenway Wash	28/27, 33/34; T 22 S, R 64 E; 480 Yards S 48° W
Gypsum var. satin spar	D-3	B.D.N.55	1/3 way down Lower Portal road, at red pillar	30/29, 31/32; T 22 S, R 65 E; 30 Yards NORTH
Gypsum var. alabaster	D-3	B.D.N.56	1/4 mile east of beach cutoff, in canyon N of highway	26/25, 35/36; T 22 S, R 64 E; 390 Yards N 50° E

Mineral Name	N. P. S. No.	C.I.T. No.	Description of Location	Location by Section Corners
Alum (potash-aluminum)	D-3 M-15	B.D.N.57	1/4 mile east of beach cutoff, in canyon N of main highway	26|25 / 35|36 T 22 S R 64 E 390 Yards N 50° E
Quartz	E-3	B.D.N.58	Near top of Sugarloaf Hill, on NE side	3/10 T 30 N R 23 W 150 Yards S 60° W
Quartz	E-3	B.D.A.59	Immediately west of main highway, about 1 mile from dam	3|2 / 10|11 T 30 N R 23 W 200 Yards S 50° W
Quartz	E-3	B.D.A.60	Halfway between Fortification Hill turnoff and mesa near river	15|14 T 30 N R 23 W 230 Yards N 50° E
Barite (plus manganese oxides)	D-4	B.D.N.61	Red Devil Claim No. 1, at base of hills W of Hemenway Wash, 1/4 mile W of bend in RR track	32|33 T 22 S R 64 E 250 Yards SOUTH
Travertine (with silica)	E-3	B.D.A.62	Top of Fortification Hill, in basalt. 100 yards N of middle of S rim	R 23 W T 31 N 24| / 25| (R 22 W) 900 Yards S 80° E
Halite	F-1	B.D.N.63	Near Overton, Nevada. Collected by Ted Werner	

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